Radiative effects of global MODIS cloud regimes

By

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Key points:

(1) Cloud systems can be organized into cloud regimes

(2) The regimes can be identified from passive observations such as MODIS

(3) The regimes have very different radiative effects that can be intercompared

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Abstract

4   We update previously published MODIS global cloud regimes (CRs) using the latest

5   MODIS cloud retrievals in the Collection 6 dataset. We implement a slightly different

6   derivation method, investigate the composition of the regimes, and then proceed to

7   examine several aspects of CR radiative appearance with the aid of various radiative flux

8   datasets. Our results clearly show the CRs are radiatively distinct in terms of shortwave,

9   longwave and their combined (total) cloud radiative effect. We show that we can clearly

10   distinguish regimes based on whether they radiatively cool or warm the atmosphere, and

11   thanks to radiative heating profiles to discern the vertical distribution of cooling and

12   warming. Terra and Aqua comparisons provide information about the degree to which

13   morning and afternoon occurrences of regimes affect the symmetry of CR radiative

14   contribution. We examine how the radiative discrepancies among multiple irradiance

15   datasets suffering from imperfect spatiotemporal matching depend on CR, and whether

16   they are therefore related to the complexity of cloud structure, its interpretation by

17   different observational systems, and its subsequent representation in radiative transfer

18   calculations.

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1. Introduction

A number of recent studies [*Rossow et al.* 2005; *Oreopoulos and Rossow* 2011; *Tselioudis et al.* 2013] have maintained that cloud information does not have to be organized along traditional "cloud type" lines, but rather that a description in terms of dominant mixtures of cloud types, known as "weather states" or "cloud regimes" is more fitting in a variety of contexts. One of the rationales behind the cloud regime concept is that traditional cloud types rarely occur in isolation in a large area $O(100\text{km})^2$ over several hours. Perhaps a dominant cloud type indeed exists, but other cloud types are frequently also present.

But how can cloud regimes be identified and defined? Passive observations often used for cloud retrievals have generally good spatial coverage, so the co-occurrence of different cloud types in a wide geographical region can be tackled adequately, as long as clouds are restricted to well-defined continuous layers. Multiple cloud types that overlap can be better identified (subject to different limitations, of course) with active observations, such as those from cloud radars and lidars. But measurements from these instruments suffer from limited spatial coverage. Passive observations have therefore been the more popular choice for compressing information about meso-scale cloud organization into regimes. The existing cloud regime literature has demonstrated that the concept makes sense for decomposing and differentiating among water and energy flux strengths and contributions of prevailing cloud formations [*Oreopoulos and Rossow* 2011; *Haynes et al.* 2013; *Lee et al.* 2013; *Oreopoulos et al.* 2014]. Furthermore, cloud regimes are more resistant to the intrusion of small random or statistically insignificant cloud property variations that confuse the interpretation of interannual variability since

24   the morphology of the full range of cloud optical properties is being accounted for

25   [Tselioudis et al. 2010; Tan et al. 2015]. But these are only some of the types of studies

26   where regimes are considered a suitable framework; more examples of possible

27   applications are given in the concluding section of *Rossow et al.* [2005].

28   This paper revisits and revises an investigation that has been attempted previously

29   as part of work with broader goals [*Oreopoulos et al.* 2014], namely the study of the

30   radiative effects and radiative importance of MODIS cloud regimes. As will hopefully

31   become apparent from what follows, the availability of new datasets makes a return to

32   this topic worthwhile. New analysis angles reveal less explored hitherto radiative

33   features, such as flux profiles decomposed by CR. Use of different data sources for

34   radiative flux information, allows intercomparisons organized in ways not shown before.

35   The presentation of the new CRs takes a big part of section 2, which also

36   documents the various datasets and methodology of use, and extends to section 3 as well.

37   The three subsections of section 4 contain the outcomes of compositing three different

38   radiative flux datasets and comparisons among them where feasible and appropriate. In

39   the concluding section 5 we find fitting to offer thoughts on lessons learned from the

40   analysis, how the findings can be used for related problems, and what new avenues of

41   investigation may be worth pursuing.

42

43   **2. CR derivation and datasets**

44   *a) Cloud Regimes*

45   The core dataset required to derive the revised MODIS cloud regimes is daily 1°×1°

46   gridded joint histograms of cloud optical thickness (τ) and cloud top pressure (p_c). We

47   use 12 years (December 1, 2002 to November 30, 2014) of such data from both the Terra

48   and Aqua satellites. The most recent version of this dataset used here known as

49   "Collection 6" (C6, henceforth) provides two major options on what type of joint

50   histograms to use: one with and one without so-called "partially-cloudy" (PCL) pixels

51   [*Zhang and Platnick* 2011*; Pincus et al.* 2012] included. In practical terms the choice

52   amounts to whether to account only for pixels surviving so-called "clear-sky restoral"

53   [*King et al.* 2006; *Zhang and Platnick* 2011] or to use all cloudy pixels for which an

54   optical property retrieval was successful, even if those were edge pixels. The reason edge

55   pixels are flagged separately as candidates for exclusion is that they are even less

56   appropriate than interior cloud pixels to be treated by the plane-parallel radiative transfer

57   model used to interpret the observed reflectances in terms of cloud optical properties of

58   uniform pixels. We opted for using the version of the histograms that includes PCL

59   pixels, motivated to some extent by the desire to match more closely climatological cloud

60   fractions in the ISCCP dataset. Such a histogram is not directly available, but can be

61   obtained by summing two types of C6 joint histograms, one without the PCL pixels and

62   one that includes only the PCL pixels. The latter histograms were not available in

63   MODIS C5.1, so the MODIS global CRs of *Oreopoulos et al.* [2014] (O14, hereafter)

64   were derived with no PCL pixels accounted for, a factor that probably contributes

65   substantially to the differences between those CRs and the ones here. With the joint

66   histograms being available only during daytime (since reflected solar radiation is needed

67   to derive τ), the CRs obtained according to the procedure described below represent

68   strictly daytime only cloud organizational structures. Of course, the joint histograms

69   include the consequences of limitations in passive observations such as the inability to

70 properly identify cloud layers obscured by clouds above, misinterpretations of some

71 multi-layer cloud scenes, and occasional strong contributions to the satellite signal by

72 certain highly reflective surfaces. In specific areas of the globe cloud property retrieval

73 errors also occur because of strong aerosol presence either above (e.g. off the west coast

74 of Africa) or between (e.g., East Asia) clouds.

75 The methodology used to derive the MODIS C6 global CRs is similar to that

76 implemented by O14, but with an important modification. The *k*-means clustering

77 method [*Anderberg* 1973] used in O14 as well as in the derivation of the ISCCP weather

78 states [*Jakob and Tselioudis* 2003; *Rossow et al.* 2005; *Tselioudis et al.* 2013) is

79 employed again, but we found empirically that more physical and robust results can be

80 obtained by starting with a small number of baseline or "core" CRs and then breaking

81 these further into "sub-regimes" as in *Mason et al.* [2014]. The number of initial core

82 regimes and the subregimes into which each may be optimally broken was determined by

83 numerous trials that tested the extent to which the criteria of *Rossow et al.* [2005] were

84 satisfied. We settled into six core regimes, and then examined whether each should be

85 further broken into two or three subregimes or whether breakdown into subregimes was

86 not needed. The basic criterion used in deciding whether a core regime should be broken

87 into two or three subregimes (or remain intact) was whether the resulting subregimes

88 differed enough from the original regime and amongst themselves. Differences were

89 quantified in terms of spatial pattern correlation coefficients between the centroids (i.e.,

90 mean joint histograms) that define a regime or subregime and the maps of their

91 geographical occurrence expressed in terms of Relative Frequency of Occurrence (RFO),

92 as defined in the papers referenced above. If both correlations were above, somewhat

93   arbitrary, subjectively-set values (0.6 for centroid patterns; 0.8 for maps), then it was

94   deemed that the subregimes were not different "enough". At the outset, each regime was

95   broken into three subregimes. If at least two out of three subregimes were similar, the

96   next iteration consisted of only two subregimes. If these two (sub)regimes were again too

97   similar, then only the original core regime was retained, i.e., a breakdown into

98   subregimes was not appropriate. The physical meaning of the latter situation is that the

99   joint histograms belonging to a CR are too similar to be grouped further into distinct sub-

100   groups. An additional factor that was taken into account was whether the process of

101   breaking into subregimes resulted in the same outcome regardless of the (random)

102   initialization of the clustering algorithm. If a large majority of the trials gave the same

103   result, then the subregime determination process was considered robust. We found in

104   practice that with only two or three subregimes being possible outcomes, repeatability of

105   results was not an issue. Note that the same criterion of insensitivity to algorithm

106   initialization was also applied to the initial core regimes.

107   The end result of the above procedure was twelve (12) CRs when all MODIS C6

108   Terra and Aqua data treated as a single ensemble. These twelve regimes resulted as

109   follows: Four "core" regimes were broken into two subregimes each, one regime was

110   broken into three subregimes, and one regime remained intact (i.e., no subregimes

111   satisfied our criteria in the latter case). Upon completion of the CR derivation procedure,

112   no distinction is retained between regimes that were originally core regimes and regimes

113   that descended from a core regime through subregime clustering, i.e., all are considered

114   CRs of equal stature. The CR pairs and triplet that have a common core CR progenitor

115   are: CR2 and CR3; CR4 and CR5; CR7 and CR8; CR10 and CR11; CR1, CR6 and

116 CR12. CR9 is the only regime that did not come from a split. Gridcell RFOs come from

117 normalization relative to the total number of regime occurrences in that gridcell, and

118 global RFOs are area-weighted averages (by cosine of latitude) of gridcell RFOs. The CR

119 indices are assigned based on the location of cloud fraction local maxima within the CR

120 centroid, so that CRs with peak cloud fractions at higher altitudes are assigned smaller

121 indices.

122 The CR centroids are shown in Fig. 1, with corresponding geographical distribution

123 of RFO in Fig. 2. The RFO and CF values for each CR in Fig. 1 as well as the maps of

124 Fig. 2 correspond to multi-annual means. Tables 1 and 3 in the supplementary material

125 provide multi-year seasonal means and separate annual means for Terra and Aqua,

126 respectively.

127 Joint inspection of Figs. 1 and 2 provides a fairly unambiguous picture of the cloud

128 mixtures represented by the twelve MODIS C6 global CRs. A basic initial description is

129 provided below, while further insight is provided in section 3 aided by additional data.

130 The regime with the largest proportion of high clouds, many of them of small

131 optical thickness, is CR1 and appears to contain a lot of the tropical cirrus associated with

132 convection, but also deeper clouds; it is arguably the most tropical of all CRs with a

133 pronounced presence in the Pacific ocean, and elsewhere within the confines of ITCZ.

134 CR2 contains most of the optically thickest clouds of all regimes, especially those

135 reaching high altitudes; it appears to comprise the strongest storm systems produced by

136 tropical and frontal convection and has the highest cloud fraction (CF) of all regimes.

137 Closely associated with CR2 is apparently CR3 which tracks tightly the geographical

138 pattern of CR2, but evidently contains the thinner elements of storm activity (in cyclonic

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139   parlance one would say that it represents cyclone sectors that are different from those

140   usually contained in CR2); presence over both land and ocean can be seen. The next two

141   regimes CR4 and CR5 appear to also be closely associated with very alike geographical

142   patterns of RFO. Bin CF peaks within the same pressure bin, but CR4 has more of the

143   optically thicker clouds and overall greater CF. These two regimes are almost exclusively

144   extratropical and are apparently dominated by alto- and nimbo- type clouds in higher

145   latitude (except for the Tibetan peak) storm systems. A closer look has shown that CR4 is

146   more prevalent during the summer months and CR5 during the winter months of the

147   respective hemisphere. CR6 is the closest of our regime set fitting the characterization of

148   a mid-level CR, and exhibits strong presence over land areas with the exception of the

149   near-polar southern latitudes and the Pacific segment of the ITCZ where it may contain

150   congestus type clouds. The next five regimes represent cloud mixtures where various

151   types of shallow and boundary layer clouds are dominant. Among this group, CR7 has

152   the optically thickest clouds and the largest CF, but also the smallest RFO (as a matter of

153   fact, the smallest RFO of all CRs); it is mainly a high latitude CR of plentiful thick stratus

154   over both lands and oceans. CR8 has occurrence peaks in known marine stratocumulus

155   areas, but also occurs in far south oceans and over northern lands. A more pure marine

156   profile characterizes CR9 which also makes a strong presence in marine stratocumulus

157   areas; its CF is similar to CR9 but appears to contain clouds that are shallower and less

158   optically thick. CR10 is also mostly marine, but its substantial lower CF compared to

159   CR9 indicates more broken stratocumulus and shallow cumulus. The latter cloud type

160   seems to be even more dominant within CR11, as suggested by small optical thicknesses

161   and low cloud fractions; this particular regime is almost exclusively oceanic with

162 negligible presence in high latitudes. Finally, CR12 comprises all 2D histograms of small

163 CF with no characteristic shapes to suggest a specific identity. It is the regime with the

164 highest global RFO and smallest CF; CRs of this type emerged not only in O14, but also

165 in the ISCCP version of global CRs derived by *Tselioudis et al.* [2013]. This regime

166 occurs almost everywhere except the nearly always overcast far southern oceans.

167   Common features, but also differences can be identified when comparing these CRs

168 to those by O14. First, there is no counterpart to CR1 in O14. CR1 in our analysis

169 emerged from the only core CR split into three subregimes. Second, low-level and

170 boundary layer cloud systems with CFs above 65% are resolved in more regimes in this

171 analysis (four here vs. two in O14). Third, the current set of regimes has only one CR

172 with peak cloudiness between 440 and 680 hPa, while in the C5.1 set of O14 there were

173 two; this is consistent with an overall drop of the mid-level cloud population in C6

174 compared to C5.1. The semi-clear low CF "shapeless" regime of this study (CR12) is

175 more populous with an RFO of ~41%, but has a larger CF (~29%) than its C5.1

176 counterpart (CF ~20%) occurring about ~31% of the time, probably because of the

177 inclusion of PCL pixels in this study. If one compares, however, the combined global

178 RFO of the two CRs with the lowest CFs (CR11 and CR12 in this study), the numbers are

179 similar: ~53% in this study compared to ~50% in O14.

180   In summary, the updated regimes now include a new high-cloud regime that did not

181 exist before, no clear-cut mid-cloud regimes, more low-cloud regimes, and a

182 "featureless" regime with higher CF and RFO than its C5.1 predecessor.

183

184 *b) Other MODIS cloud variables*

185   In addition to the p_c-τ joint histograms we also use other MODIS cloud variables from

186   Level-3 daily 1° gridded data which are composited by CR and are sometimes used only

187   for internal diagnostic and interpretation purposes (one such use was guidance for the

188   subregime analysis). Such variables are liquid and ice CF of successful MODIS

189   retrievals, mean combined τ (also available by cloud thermodynamic phase), and mean

190   p_c. Individual and composite values for all these variables are calculated with PCL pixels

191   accounted for consistency with the joint histograms used in the CR derivation.

192

193   *c) CERES radiative fluxes*

194   We use two types of SYN1deg Edition 3A CERES radiative fluxes to examine the

195   radiative behavior in terms of the Cloud Radiative Effect (CRE) (defined later) of the

196   new global MODIS CRs. Both products are gridded at 1°, but one is diurnally (24-hour)

197   averaged (SYN1deg-daily) while the other represents 3-hour averages (SYN1deg-3hr).

198   The SYN1deg products use 3-hourly geostationary (GEO) satellite radiances and cloud

199   properties to more accurately model the diurnal variability between CERES (Terra and

200   Aqua) observations. The Top-Of-the-Atmosphere (TOA) fluxes (all-sky and clear-sky)

201   are temporally interpolated from observed fluxes at the time of CERES overpasses using

202   the GEO information [*Doelling et al.* 2013]. Surface (SFC) fluxes come from a

203   broadband radiative transfer code which uses as input MODIS and GEO cloud properties,

204   atmospheric profiles provided by the Goddard Modeling and Assimilation Office

205   (GMAO), and MODIS aerosols [*Rutan et al.* 2015]. Compositing CERES CREs (and all

206   other variables for that matter) by regime essentially amounts to deriving an area-

207   weighted global average from all CRE values that coincide spatiotemporally with a given

208   regime occurrence. The details of the compositing and the distinctive treatment of the two

209   CERES products will be provided in the appropriate results subsection. The length of the

210   CERES datasets is the same as that of the MODIS CR, i.e., December 1, 2002 to

211   November 30, 2014.

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213   *d) CloudSat-CALIPSO-based radiative fluxes*

214   The radiative products from CloudSat and CALIPSO (hereafter often referred to

215   collectively as "CC") composited as a function of MODIS CR come from the 2B-

216   FLXHR-LIDAR (R04) dataset. This dataset is produced from an algorithm that builds off

217   the predecessor 2B-FLXHR algorithm [*L'Ecuyer et al.* 2008] by taking advantage of

218   recent improvements in cloud and precipitation products and by explicitly accounting for

219   clouds and aerosols not detected by CloudSat itself [*Henderson et al.* 2013]. The unique

220   feature of the dataset is its full profiles of radiative flux coming from radiative transfer

221   calculations applied to vertical profiles of cloud properties retrieved from CC

222   observations [*L'Ecuyer et al.* 2008; *Henderson et al.* 2013]. A clear-sky radiative flux

223   profile is also provided (obtained by a second radiative transfer calculation where cloud

224   is removed while everything else remains the same), which allows thus calculation of

225   CRE profiles. Since the CC duo is part of the A-Train [*L'Ecuyer and Jian* 2010] of which

226   Aqua is also a member, we composite radiative flux (CRE) profiles for the 1:30 pm CC

227   overpass and only for CR occurrences at that time, i.e., from Aqua. Specifically, we

228   combine (average) all 1:30 pm irradiance profiles that fall into the 1° gridcell that

229   contains a particular Aqua CR occurrence. The flux/CRE profiles are available for both

230   the LW and SW spectral domains. Similar compositing is applied to two CRE variables

231   provided separately, TOACRE and BOACRE (for top and bottom of the atmosphere,

232   respectively). These two CREs assume slightly different values than those obtained by

233   subtracting clear and all-sky values for the topmost and lowest level (valid) values of the

234   flux profile.

235   When converting CREs to a measure of cloud impact on heating rates (see eqs. 3

236   and 4 that follow), atmospheric density profiles are needed. These can be calculated from

237   atmospheric variables provided in the ECMWF-AUX CloudSat product. The ECMWF-

238   AUX dataset is an intermediate product that contains the set of European Center for

239   Medium-Range Weather Forecasts (ECMWF) state variables interpolated to each

240   CloudSat Cloud Profiling Radar (CPR) bin from the ancillary AN-ECMWF analysis

241   dataset.

242   The time period covered by the 2B-FLXHR-LIDAR and ECMWF-AUX datasets is

243   January 1, 2007 to December 31, 2010 (four years).

244

245   *e) AIRS radiative fluxes*

246   LW radiative fluxes at the TOA (also known as Outgoing Longwave Radiation – OLR) at

247   the time of the Aqua satellite overpass are likewise available in the AIRS V6 Level-3

248   dataset also on a 1° grid. These come from radiative transfer calculations that use

249   information from the AIRS/AMSU (Atmospheric InfraRed Sounder/Armospheric

250   Microwave Sounding Unit) instrument suite [*Pagano et al.* 2003] aboard Aqua (hereafter

251   simply referred to a "AIRS"). Details on how these irradiances are derived can be found

252   in *Susskind et al.* [2012]. In simple terms, AIRS-derived profiles of temperature,

253   humidity, ozone, carbon dioxide, and surface skin temperature, as well as cloud

254 properties are used as input into the radiative transfer code RRTMG-LW [*Iacono et al.*

255 2008] which produces irradiances at desired atmospheric levels. A clear-sky flux

256 calculation is also made separately, so CRE can be assessed again the usual way (see eq.

257 1 that follows). We use only the flux calculation from the 1:30 pm (daytime) Aqua

258 overpass, since CRs are available only during daytime. The time period covered by the

259 AIRS CRE LW dataset is the same as that for the MODIS CRs, i.e., December 1, 2002 to

260 November 30, 2014.

261

262 **3. Additional insight into the MODIS CRs**

263 The interpretation of the CRs provided in subsection 2a is consistent with the dynamical

264 environment in which CRs are embedded, at least as represented by the large-scale

265 vertical velocity at 500 hPa. This velocity is commonly obtained by re-analysis.

266 Following this established practice we choose MERRA [*Rienecker et al.* 2011] re-

267 analysis data for performing a CR-based compositing of pressure velocity. Fig. 3 shows

268 the outcome of this exercise in the form of a boxplot. The clear pattern seen in the figure

269 supports the choice of the term "weather state" [*Rossow et al.* 2005] for what we call here

270 CR. While our index assignment was blind to the dynamical environment, we see that it

271 is quite effective in organizing regimes in terms of large-scale vertical motion: the first

272 six CRs occur in areas where the mean (and median) vertical velocity indicates ascending

273 motion, while the six CRs assigned the highest indices occur in areas where descending

274 motion at 500 hPa prevails. CR2, containing the thickest and deepest clouds occur in

275 environments of strongest ascent; while the ascent is weaker for CR4 and CR5, these

276 regimes still occur in environments virtually devoid of large-scale descending motions in

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277 the mid-troposphere. For CR7-CR11, regimes with abundant shallow and boundary layer

278 clouds, descending motions dominate. Low CF CR12, containing no clear dominant

279 cloud type and being omnipresent, is similarly ambiguous in terms of its dynamical

280 environment which exhibits near equal amounts of large-scale descent and ascent. Other

281 atmospheric indicators can of course be invoked to describe the environment in which

282 CRs are embedded, even including sophisticated representations within joint dynamical-

283 thermodynamical phase spaces, but we limit ourselves to large-scale vertical motion as a

284 signifier of atmospheric information content implicitly residing in p_c-τ histograms.

285 Simply put, the clustering algorithm applied to such joint variations appears to be quite

286 skillful in deriving meaningful modes of cloud organization.

287 The CR concept by design encourages dismissal of standard cloud discrimination

288 conventions based often on naïve criteria such as cloud thermodynamic phase.

289 Nonetheless, Fig. 4 shows that our CRs have clear thermodynamic phase traits, with most

290 CRs assuming a predominant (in terms of cloud fraction) liquid or ice phase identity.

291 Only CR4 and CR12 are relatively balanced in terms of their ice and liquid cloud

292 fractions. The first three CRs, not surprisingly given their large proportions of high

293 clouds are dominated by ice phase clouds. CR5, also consists mostly of ice clouds; recall

294 that we identified this CR as the winter doppelgänger of the "summer" CR4 which

295 naturally contains more liquid than ice clouds. CR7-CR11 encompass mostly liquid

296 clouds consistent with centroids exhibiting peaks at high atmospheric pressures (low

297 altitudes). It is less easy to predict the dominant thermodynamic phase of CR6 from the

298 appearance of the centroid alone, but it turns out that it too consists mostly of liquid

299 clouds, at least according to the MODIS phase discrimination algorithm.

300   A more traditional breakdown of CRs by cloud type is shown in Fig. 5. What is less

301   traditional is the way the proportion of each cloud type was derived and how the cloud

302   types were identified. Specifically, they come from the CloudSat 2B-CLDCLASS

303   dataset, i.e., from a sorting and classification of active CPR observations. We used the

304   form of the dataset aggregated in the merged CERES/CloudSat/CALIPSO/MODIS

305   (CCCM) product [*Kato et al.* 2010; 2011]. A similar breakdown with the same dataset

306   was also shown in O14. Examination of Fig. 5 indicates a general consistency between

307   active (2B-CLDCLASS) and passive (2D MODIS histograms) cloud views. The fraction

308   of *Sc* clouds (given the absence of *St* in meaningful amounts in the 2B-CLDCLASS

309   product) serves as a good indicator of affinity with Fig. 4, as well as the various centroid

310   panels of Fig. 1 (a cloud type abbreviation key is provided in the caption of Fig. 5). CR7-

311   CR11 have the largest fraction of *Sc*, re-affirming their shallow and boundary layer

312   character. CR2, embedded in the strongest large-scale ascent environments has the most

313   *Cb*'s, while CR1 has most *Ci* than any other regime in accordance with what is visually

314   conveyed by its centroid. If the fraction of high- and mid-topped clouds were to be

315   inferred by the sum of *Cb*, *Ci*, *As*, and *Ac* fractions, then the first three CRs are in a

316   category of their own, with about 70% of their composition coming from such clouds.

317   CR4, CR5, and CR6 have the largest fraction of *Ns*. While CR4 and CR5 cannot be

318   discriminated by their combined fraction of *Sc* and *Cu*, CR4's more stormy nature is

319   exposed by more *Ns* and *Cb* clouds. Fig. 5 also confirms that CR12 is hardly a cloud

320   regime with only shallow clouds; as its centroid suggests, high proportions of mid- and

321   high-level clouds are also found, albeit in small absolute numbers since the CF of the

322   regime is so low.

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4 CR Cloud Radiative Effects

a) From CERES

For our basic results we largely follow previous choices and practices on how to present CR radiative effects in terms of CRE. The gridcell CRE (for either the LW or SW or part of the spectrum, and for *total*=LW+SW) is defined here as:

$$CRE = F_{all-sky} - F_{clr} = A_c(F_{ovc}[f(p_c, \tau)] - F_{clr}) \tag{1}$$

where $F_{all-sky}$ is the radiative flux for a mixture of clear and cloudy conditions within the gridcell, F_{ovc} (mainly a function of p_c and τ) is the radiative flux (irradiance) of overcast skies, F_{clr} is the corresponding flux for "clear" (cloudless skies), and A_c is the gridcell cloud fraction (reserved for the gridcell value, as opposed to the physical variable CF).

When using the SYN1deg-daily data we composite (i.e., average globally using latitude as weight) only gridcells occupied by the same CR for both Terra and Aqua; these special gridcells represent 25.4% of the total number of gridcells analyzed ($\sim$435.5$\times$10^6). This approach was discussed in O14 as essentially the best available (but certainly imperfect) criterion for identifying persistence of a particular CR within a gridcell. Except for this condition, the compositing is rather straightforward since both the CR and the CERES SYN1deg-daily dataset are available at the same temporal (one-day) and spatial (one degree) resolution and for an identical time period. Results shown in Figures 6-8 convey three basic results, the position of each CR in SW/LW/*total* TOA CRE space, the percent contribution of each CR to the total SW/LW/*total* planetary TOA CRE, and the contrast between the LW CRE at the TOA and SFC which provides insight

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345   on each CR's average radiative cooling or warming effect on the atmosphere (the trivial

346   SW warming effect across all CRs is not shown). Net fluxes (down $F^{\downarrow}$ minus up $F^{\uparrow}$) are

347   used in Eq. (1) to derive the results shown in these figures. When using net fluxes LW

348   CRE assumes almost always positive values while SW CRE negative values at both TOA

349   and SFC. The information content of these three figures will be discussed in some detail

350   next.

351   The salient information content of Fig. 6 is the average radiative strength at the time

352   of regime occurrence. CR2 and CR4 stand out, with CR2 having the most pronounced

353   radiative effects of the two in both the LW and SW part of the spectrum. This comes as

354   no surprise given that CR2 has large fractions of clouds that have both high tops and

355   large optical thicknesses. The notable drop of LW CRE from CR2 and CR4 is of course

356   related to cloud populations in CR4 with overall lower cloud-top altitudes. Differences in

357   the SW CRE averages, on the other hand, come from slightly smaller overall optical

358   thicknesses in CR4 and locations of occurrence that receive lower illuminations overall.

359   Incoming solar radiation plays again a big role (in addition to cloud optical thickness and

360   cloud fraction) in the huge difference between the SW CREs of CR4 and CR5 despite

361   maps of (multi-) annual RFO that look very similar. As has been discussed earlier, CR5 is

362   predominantly a winter and CR4 a summer regime. CR7 and CR9 have similar (and quite

363   strong) SW CRE and small LW CRE (higher cloud tops give an edge to CR7) consistent

364   with their perceived image as extensive (in terms of CF) and relatively thick low-level

365   clouds. The next group of CRs roughly consisting of CR1, CR3, CR6, and CR8 have

366   mean SW CREs that are about 20 Wm^{-2} lower (in absolute values), but exhibit an

367   extremely wide range of LW CRE reflecting large differences in cloud top altitudes

18

368 prevalent within those regimes. CR10, CR11, and CR12 straddle similar low values of

369 LW CRE due to combinations of low CFs and lack of high clouds in sufficient numbers;

370 CR10 seems to have thicker clouds and greater CF than the other two, and thus separates

371 in terms of SW CRE.

372   CR12 is the only CR that has near zero net CRE, with all other regimes exhibiting a

373 vast range of negative values and therefore exerting varying degrees of radiative cooling

374 effect on the earth-atmosphere system (note that SW cooling is realized at the surface and

375 LW cooling or warming mainly within the atmosphere). The largest cooling effect does

376 not come from CR2, the regime with the highest individual LW and SW CRE values, but

377 from the low-cloud dominated CR9, followed closely by CR7 and CR4. Even CR1 with

378 its many cirrus clouds has an overall negative net CRE despite positive values occurring

379 in about 47% of the samples used to determine the CR1 mean in this plot.

380   The global TOA CRE numbers from the special sample used here (gridcells that

381 have the same CR for both Terra and Aqua) are largely consistent with figures published

382 previously [*Harrison et al.* 1990; *Zhang et al.* 2004; *Stephens et al.* 2012; *Henderson et

383 al.* 2013]. Our global SW CRE is -46.2 Wm^{-2} and our LW CRE 26.1 Wm^{-2}, values

384 derived by taking a weighted average of individual CR CRE means, with CR global

385 RFOs serving as weights.

386   The variability of CRE values is depicted by the horizontal and vertical error bars

387 which represent (one fifth of) the interquartile range of the distribution used to calculate

388 the composite means. The error bars therefore provide guidance on how wide the

389 distribution of CRE values is for each CR, and not on the uncertainty of the means.

390 Seasonal changes in solar illumination contribute greatly, of course, to the SW CRE

391   variability. But the CRE variability is also a strong function of the dominant CRE

392   magnitudes in the distribution (regimes with small overall CRE such as CR10, CR11, and

393   CR12 have also small interquartile ranges). The only regimes with comparable SW and

394   LW interquartile ranges are CR1 and CR3; of the two, CR1 has also almost equal mean

395   SW and LW CRE values. The low-cloud dominated regimes CR7 and CR9 have very

396   large SW CRE variability, but negligible LW CRE variability.

397   While Fig. 6 distinguishes radiatively strong and weak regimes at the time of

398   occurrence, what eventually matters from an energetics perspective is a CR's overall

399   radiative contribution which also depends on its frequency of occurrence (RFO). The role

400   of RFO is incorporated in the results of Fig. 7 because the percent contributions of CRE

401   shown in this figure were calculated by dividing the sum of all CRE values corresponding

402   to a CR to the sum of all available CRE values (subject to the sampling strategy for

403   CERES SYN1deg- daily data discussed earlier). In this representation, the radiative

404   contributions of the previously weak CR12 are so large, because of its huge RFO, that a

405   special insert into the plot is required: CR12 contributes about 39% of the global LW

406   CRE and ~24% of the SW; but it has a far less remarkable ~6% contribution to *total* CRE

407   because of its near-zero average *total* TOA CRE. CR1, CR3, and CR5 stand out for their

408   even smaller *total* CRE contributions, even though the first two have quite large SW and

409   LW contributions; this is because they belong to the group of CRs with small average

410   *total* CRE (Fig. 6). CR2, the strongest regime in terms of average CRE, falls fourth when

411   CRE contributions are examined because of its unimpressive RFO. Low-cloud dominated

412   CR9 has the distinction of largest discrepancy between LW and SW CRE contributions:

413   its relative contribution is three times larger in the SW than the LW.

414   O14 demonstrated a rather unambiguous separation of MODIS C5.1 CRs into those

415   that radiatively warm and those that cool the atmosphere. We have now updated those

416   results in Fig. 8 and again focus on only the LW part of the spectrum since the SW effect

417   is known to be a small nearly universal warming (cloud presence contributes a small

418   additional amount of atmospheric absorption). When the LW CRE at SFC is greater than

419   the LW CRE at TOA clouds have a cooling effect on the atmosphere and vice-versa.

420   With the exception of CR12 which sits on the diagonal of zero atmospheric radiative

421   effect, the regimes separate quite well into radiative warmers and coolers. Those above

422   the diagonal (cooling) have the largest proportions of low clouds, while those below the

423   diagonal (warming) have many high clouds. CR7, CR8 and CR9 are the regimes with the

424   more prominent cooling, while CR1, CR2, CR3 induce the highest radiative warming.

425   The overall result (taking the RFO-weighted average) of 0.75 Wm^{-2} from the sample used

426   here suggests a near balance between cloud-induced cooling and warming, consistent

427   with previous results: *Henderson et al.* [2013] found a slight warming of ~1.5 Wm^{-2} ,

428   while the ISCCP-based results of *Zhang et al.* [2004] and our own analysis of CERES

429   EBAF (Energy Balanced And Filled) data indicate a slight cooling of approximately -3

430   Wm^{-2}. Despite the SW CRE (warming) effect being small, its additive nature (no

431   cancellations as in the LW) brings the cloud global *total* atmospheric CRE to ~3 Wm^{-2}, a

432   value, once again, that is specific to the data sample used here.

433   Similar to Fig. 6, we include information about the variability of the LW CRE

434   values in terms of interquartile range values (1/2 of the actual value is shown for clarity).

435   The CRs below the diagonal with CRE at TOA greater than at the SFC tend to also

436   exhibit greater variability in TOA CRE; the opposite happens for the CRs above the

437 diagonal. An extreme example of strong TOA CRE variability and almost no SFC CRE

438 variability is CR1 which occurs largely in the tropics where the LW effect of clouds at

439 the surface is small and barely variable given how strongly the downwelling LW flux is

440 modulated by near-surface atmospheric temperatures in very humid environments.

441   The SYN1deg-3hr dataset offers the means to examine radiative impacts of Terra

442 and Aqua CR occurrences separately. Basically, a similar analysis as with the SYN1deg

443 daily dataset can be conducted, but with matching in this case a Terra or Aqua CR

444 occurrence with the 3-hr average CERES flux of the same gridcell that contains the

445 appropriate daytime satellite overpass. We compare Terra and Aqua CRE breakdown in

446 Fig. 9: the top two panels show the magnitudes of SW and LW CRE while the bottom

447 two panels show the percent contributions to the global Terra and Aqua CRE. A SW CRE

448 magnitude comparison is apt because of insolation symmetry around local noon (subject,

449 of course, to the coarse 3-hour temporal resolution of the CERES dataset).

450   CR2, the regime with the largest mean values of LW and SW CRE is also the

451 regime with the largest Terra-Aqua discrepancy. This is not the case for contributions,

452 where CR2 ranks lower. Both in terms of absolute magnitudes and contributions, the

453 Aqua value is larger, consistent with the expectation of stronger convection during

454 afternoon hours. In general Aqua LW CRE is greater for regimes CR2 to CR5, all in the

455 top-5 of strongest LW CREs. Interestingly, SW CRE is not as distinct between Terra and

456 Aqua for CR3 and CR5 (although contributions for these regimes are bigger for Aqua);

457 this makes it less likely that morning-afternoon differences in LW CRE come from CF

458 changes (a conclusion confirmed by Supplementary Material Table 3 which shows small

459 CF differences on an annual basis). The regimes with cloud populations consisting

460 mainly of low clouds show almost no differences in (already low) LW CRE, but three of

461 them, CR7, CR8, CR9 exhibit notable differences in SW CRE. For CR9, the difference in

462 the magnitudes themselves translates to almost no contribution difference; for the other

463 two regimes, however, larger Aqua SW CRE means are apparently not enough to

464 translate to bigger relative contributions to the Aqua global CRE; the importance of these

465 regimes is therefore bigger for the Terra global SW CRE. In general, when comparing

466 regimes in terms of relative CRE strengths, we see consistency between the LW and SW

467 parts of the spectrum, in the sense that regimes with bigger contribution imprints for

468 Terra compared to Aqua maintain that feature for both parts of the spectrum: CR2, CR3,

469 CR4, CR5 matter more in the afternoon for both LW and SW CRE, while CR1, CR7,

470 CR8, and CR12 matter more in the morning (for all other regimes differences are less

471 noteworthy).

472

473 *b) From CloudSat-CALIPSO*

474 Despite being based on more spatially limited observations and providing imperfect areal

475 matching with our other radiation datasets, the 2B-FLXHR-LIDAR product [*L'Ecuyer et*

476 *al.* 2008; *Henderson et al.* 2013] which comes from application of radiative transfer

477 calculations on cloud retrievals from active CC observations, enables an enriched

478 perspective on the radiative effects of CRs. Specifically, this dataset allows examination

479 of regime radiative impacts throughout the depth of the atmosphere either in terms of

480 CRE or as cloud effects on the atmospheric heating/cooling rates of atmospheric layers.

481 A measure of the latter is the difference between all-sky and clear-sky heating/cooling

482 rates called here Cloud Radiative Heating (*CRH*) following *Haynes et al.* [2013]:

23

483
$$CRH = \left(\frac{dT}{dt}\right)_{all-sky} - \left(\frac{dT}{dt}\right)_{clr} \qquad (2)$$

484 where

485
$$\frac{dT}{dt} = -\frac{1}{\rho C_p}\frac{dF}{dz} \approx -\frac{1}{\rho C_p}\frac{\left[\left(F^{\downarrow}(z)-F^{\uparrow}(z)\right)-\left(F^{\downarrow}(z+\Delta z)-F^{\uparrow}(z+\Delta z)\right)\right]}{\Delta z} \qquad (3)$$

486 so that

487
$$CRH = -\frac{1}{\rho C_p}\frac{dCRE}{dz} \approx -\frac{1}{\rho C_p}\frac{CRE(z)-CRE(z+\Delta z)}{\Delta z} \qquad (4)$$

488 T, ρ (from ECMWF-AUX), C_p, z, t, are the air temperature, air density, specific heat of

489 dry air under constant pressure, altitude, and time. With an appropriate scaling factor,

490 *CRH* can be expressed in units of K/day. Note that the reliability of CRH is somewhat

491 tarnished by the nature of the calculation where eight distinct fluxes (four clear and four

492 cloudy at the layer boundaries) are used.

493 We first look at CRE profiles partitioned by CR. The plots show profiles of CRE

494 for upward, downward as well as net (down minus up) flux separately for the LW (Fig.

495 10) and SW (Fig. 11) part of the spectrum. The profiles were calculated by averaging the

496 valid flux values belonging to a CR for each of the 125 vertical layers followed by height

497 assignment for each layer by taking the mean of all heights corresponding to that layer

498 (because the height of a layer differs by location). Given the definition of CRE by eq. (1),

499 the profile of LW CRE retains negative values for upward flux, and positive values for

500 downward and net fluxes. The opposite occurs for SW: upward CRE is positive, while

501 downward and net CRE assume negative values. Because the downward LW CRE is zero

502 at TOA and so is the upward LW CRE at SFC, the net LW CRE equals the upward CRE

503 at TOA (in absolute values) and the downward CRE at the SFC. Virtually opposite

504 behavior is seen for the SW, the only difference being that the upward SW CRE at the

505 SFC is slightly different from zero because of different SFC upwelling flux under clear

506 and cloudy skies; the end result is that the downward and net SW CRE at the SFC are not

507 exactly identical, while the upward SW CRE at TOA matches exactly the net CRE in

508 absolute values.

509   The CRE plots for LW are probably more intriguing than those for SW. The LW

510 profiles exhibit progressively less structure as one moves from low to high index CRs.

511 The main guiding principle to keep in mind when examining these plots is that a value at

512 a particular level in the upward CRE profile represents the cumulative effects of all

513 clouds below, while for the downward CRE profile it represents the cumulative effect of

514 the clouds above. The shape of the upward and downward CRE profiles therefore reflects

515 the configuration of the vertical locations of cloudiness within each CR, with the more

516 prominent features associated with locations of peak cloudiness. One difference between

517 the two profiles is that the upward CRE profile is monotonic, i.e., values increase in an

518 absolute sense from SFC towards TOA; the downward CRE profile on the other hand

519 exhibits a peak at some level within the atmospheric column. The former behavior can be

520 explained by the larger opacity of cloudy compared to clear skies and the fact that

521 average tropospheric temperature drops with altitude: as one moves upward the contrast

522 between clear and cloudy sky in terms of the cumulative effects of the atmospheric layers

523 below always increases (i.e., the radiative emission height of cloudy skies moves more

524 rapidly upwards, toward colder temperatures, than in clear skies, given that cloudy

525 opacity grows faster than clear sky opacity) widening thus the contrast between clear and

526 cloudy flux. In the case of the downward flux the LW CRE will inexorably start to

527 decrease towards lower altitudes at some height as the contrast in downward cumulative

528   opacity (which moves the emission height for downward flux to lower levels) is

529   compensated by temperature increases towards lower altitudes. In other words the

530   distance between clear-sky and cloud-sky emission height after reaching a peak,

531   decreases once additional cloud opacity is exhausted. The net LW CRE profile being the

532   difference between the downward and upward CRE profiles, i.e., something akin to a

533   CRE "divergence", mirrors more closely the downward CRE profile or the upward CRE

534   profile (in absolute value) towards the boundary of the atmospheric column where each

535   component is dominant, while it peaks where the two CRE profiles diverge the most.

536   Note that the upward and downward LW CRE profiles exhibit a progressive

537   decrease of the height level where CRE saturates (upward) or reaches its peak

538   (downward) as the CR index increases. This is a consequence of the general downward

539   shift of cloudiness in our CR ordering. There are a few CR pairs that cannot be

540   distinguished easily on the basis of their LW CRE profiles alone: CR4 and CR5; CR7 and

541   CR8; CR10 and CR11. So while there are plenty of characteristics that make the

542   members of these CR pairs distinct, the LW CRE profile is not one of them.

543   The SW CRE profiles (Fig. 11) are somewhat more straightforward to interpret, but

544   also less intriguing. Upward and downward CRE profiles have similar shapes that follow

545   each other closely with the exception of the atmospheric layers close to the surface where

546   the downward CRE reduces (in absolute terms) slightly but abruptly probably because of

547   water vapor reducing the contrast between downward clear-sky and all-sky fluxes. The

548   change in slope for both profiles occurs where there is enough cloud of substantial optical

549   thickness, and can be understood more easily by focusing on the downward CRE: the

550   TOA value of zero remains intact until the topmost cloud layers are encountered by the

551 downward solar beam at which point the transmitted solar radiation for cloud-covered

552 skies is drastically reduced. This interpretation helps us understand the progression of

553 CRE profile "bending" points as one moves from high-cloud-rich to low-cloud-rich CRs.

554 The reason a bending point is harder to identify for CR1 is because its upper level clouds

555 are optically thinner and the reduction in downward solar radiation less dramatic.

556 Because of the near-constant difference between the downward and upward CRE, the net

557 CRE profiles are quite shapeless and hard to associate with cloud presence. An additional

558 reason for the apparent featureless appearance of the net profiles is the use of the same

559 scale as for the up and down CRE profiles. Yet, the variation with height of the net CRE

560 profile is what determines CRH per eq. (4), and further explained below.

561   The LW and SW CRH profiles for each CR are shown in Fig. 12. Once again, the

562 physical meaning of these profiles is that they show how much additional heating or

563 cooling clouds provide to the atmosphere. As eq. (4) indicates, CRH is proportional to the

564 derivative of the net CRE profiles, i.e. to the slope profile of the black curves of Figs. 10

565 and 11. As pointed out earlier, clouds provide additional heating of the atmosphere in the

566 SW overall. Cooling contributions (negative values of CRH), however, are also seen, and

567 they occur below the bulk of cloud occurrence characteristic of each regime. The levels at

568 which cooling starts to occur (when descending from high to low altitudes) therefore shift

569 as one progressively moves from high-cloud regimes (low CR indices) to low-cloud

570 regimes (high CR indices). The cooling is of course explained by the reduction of solar

571 radiation available to be absorbed by the water vapor underneath the bulk of cloudiness.

572 The peak of positive CRH (heating) happens at the altitudes of local maximum in CF and

573   τ as long as a large fraction of the downward solar beam has survived its encounter with

574   the clouds above.

575   The LW CRH curves of Fig. 12 also provide insight on how cloud-induced heating

576   or cooling of the total atmospheric column inferred from Fig. 8 is achieved. The regimes

577   below the diagonal in Fig. 8, CR1-5, characterized previously as warming regimes,

578   realize the warming below the levels where most of the clouds occur and exhibit cooling

579   above. The cooling regimes, CR6-11 exhibit cooling throughout most of the atmospheric

580   column with peaks occurring near the top of where most of the cloudiness resides. The

581   results shown here are not directly comparable to those of *Haynes et al.* [2013] who show

582   latitude-height distributions of CRH, but are largely consistent if one considers the

583   preferred areas of occurrence of our regimes.

584   The comparison between 2B-FLXHR-LIDAR LW CRE at TOA and CERES is left

585   for the next subsection where AIRS TOA LW CRE is added as another comparison point.

586   Here (Fig. 13) we show in step plot form only the comparison between LW and

587   normalized SW CREs at the SFC (the SW TOA result does not provide much additional

588   insight). The 2B-FLXHR-LIDAR variable used is BOACRE. Normalization is achieved

589   simply by taking the ratio of standard CRE to incoming insolation at TOA. The CERES

590   values come from the SYN1deg-3hr dataset with the 3-hour data point containing the

591   selected 1:30 pm CC observation. The rationale for normalizing the SW CRE is to

592   remove first order differences in the amount of incoming solar energy caused by the

593   imperfect temporal matching.

594   The top panel of Fig. 13 summarizing the LW SFC CRE comparison reveals

595   notable discrepancies between the two datasets for certain CRs. 2B-FLXHR-LIDAR

596 values tend to be larger for the CRs dominated by high cloud, the exception being the

597 tropical CR1 where the values of SFC CRE are low because of its strong decoupling from

598 cloud presence given the very humid environment. As we will see later, the discrepancy

599 remains in the same direction also at TOA for these CRs. However, the difference

600 between the two CREs reverses signs as more low clouds appear in higher index CRs. It

601 is interesting to compare CRE contrasts among certain CRs internally within the two

602 datasets. For instance the contrast between CR2 and CR1-CR3 is quite larger for

603 CloudSat/CALIPSO than for CERES; but the former dataset exhibits much less contrast

604 than the latter when CR6 is compared to CR5-CR7. Because SFC flux estimates involve

605 radiative transfer calculation for both datasets, the specifics of cloud input (which come

606 from different measurements) matter greatly for the eventual CRE values. CRs with low

607 cloud fraction and simpler cloud structures, and therefore fewer ambiguities in the

608 interpretation of the cloudy scene between active and passive measurements, have

609 smaller disagreements in SFC LW CRE. One should also keep in mind that passive

610 measurements have in general lower skill in locating cloud base altitude, a major driver

611 of SFC LW CRE.

612 Turning our attention now to the comparison of normalized (as described above)

613 SW SFC CRE, we note quite substantial inconsistencies for several regimes (CR1 to

614 CR4; CR7 and CR9). The inconsistencies should not be surprising given the

615 interpretation of (imperfectly matched in space and time) cloudiness by different

616 observation systems, as explained above. Moreover, while the normalization accounts for

617 the different amounts of incoming solar energy, it does not correct for the dependence of

618 cloud reflectance and (more relevant for this case) transmittance on solar zenith angle.

619   Nevertheless, besides the aforementioned CRs, the agreement in normalized SW SFC

620   CRE is remarkable, and may be even fortuitous to some extent. The ordering of CR

621   strength with respect to this particular CRE measure is almost the same between the two

622   datasets; the sole exception is the opposite direction seen when going from CR8 to CR9.

623   In general, CRs are less distinct radiatively for CC. As characteristic examples, consider

624   the much smaller contrasts for CC between CR7 and CR8 (and also CR5-CR6) and

625   between CR9 and CR10 (the contrast between CR9 and CR8 being larger than CERES is

626   the notable exception).

627

628   *c) From AIRS*

629   The different radiative behavior of the various CRs in the thermal infrared spectral region

630   can also be gleaned by instantaneous values of LW TOA CRE inferred from the AIRS

631   OLR product discussed in subsection 2e. Fig. 14 compares then three LW TOA CRE

632   datasets, all for Aqua CR occurrences: CERES-SYN1deg-3hr (from the data points

633   containing the 1:30 pm observations of CC and AIRS), 2B-FLXHR-LIDAR, and AIRS.

634   Now we show the comparison in the form of a scatterplot with the CERES values on the

635   x-axis used as "reference" for the purposes of the discussion. CERES and AIRS cover the

636   same 12-year period, while 2B-FLXHR-LIDAR a much shorter period of four years. A

637   systematic pattern can be immediately seen: blue points (AIRS) tend to appear below the

638   black diagonal, indicating values lower than those from CERES, while the opposite is

639   seen for 2B-FLXHR-LIDAR data. The differences tend of course to be smaller in

640   absolute value for the low-cloud dominated regimes for which the LW CRE is weaker.

641   For CR2, the regime with the strongest LW CRE at TOA, the AIRS-CC discrepancy is

642 quite large, about ~25 Wm^{-2} with AIRS differing slightly more from CERES than CC

643 despite interannual variations not being a factor.

644   Part of the discrepancies between CERES and the other two datasets can be

645 attributed to the fact that the CERES values are not strictly speaking 1:30 pm values, but

646 three-hour averages around that point in time. But this does obviously not explain why

647 AIRS and 2B-FLXHR-LIDAR tend to be on opposite sides of the diagonal since the

648 observations are almost exactly contemporaneous (although imperfectly collocated

649 spatially – something that would produce random differences). Since for both these

650 datasets CRE comes from radiative transfer calculations that use as input different

651 interpretations of cloudiness within their field of view, one from passive infrared

652 measurements, the other from active observations, it may not come as a surprise that the

653 biggest discrepancies occur for the regimes, like CR2, with the most complex cloud

654 structure.

655   The systematically lower values of AIRS prompted us to conduct additional

656 investigation. Specifically, we looked at AIRS OLR availability as a function of MODIS

657 gridcell A_c values for each CR. We found that the fraction of available AIRS OLR values

658 given the existence of a MODIS CR decreased with A_c. This is apparently related to the

659 progressively reduced ability to retrieve temperature and moisture profiles (needed for

660 the radiation calculations that produce the OLR and hence CRE) as AIRS footprints

661 become more cloudy [*Tian et al.* 2013]. When $A_c > 0.9$ in the 1°×1° gridcell, an AIRS

662 OLR was available only 82% of the time. The availability fraction of AIRS OLR in this

663 CF range is much less for certain CRs, notably CR1, CR2, and CR11 with availability

664 fractions of 0.59, 0.65, and 0.63 respectively. Given the linear dependence of gridcell

665   CRE to A_c per eq. (1), it is not surprising that the many missing OLRs at the highest CFs

666   make the AIRS LW CREs to be biased toward smaller values.

667   With CC- and AIRS-based LW TOA CREs being systematically, higher and lower

668   than CERES, respectively, an obvious question is whether the ranking of CRs in terms of

669   their contribution to the global CRE is affected. The answer can be sought in Fig. 15

670   which is a scatterplot similar to that of Fig. 14, but with percent contributions plotted this

671   time. There is no doubt about the two CRs with the strongest contributions, shown

672   separately in the inset. All datasets agree on the contribution values of CR12 which is

673   driven forcefully by this regime's dominant RFO; but CR3 is more important for AIRS

674   than for the other two datasets. For the third ranked CR there are interesting differences

675   among the datasets: it is CR2 for 2B-FLXHR-LIDAR, far exceeding CR1, which tops

676   CR2 for AIRS, but with less contribution contrast; for CERES, however, these two

677   regimes contribute about the same. CR4-CR5 are little different for 2B-FLXHR-LIDAR

678   and CERES, but more different, and with order reversed, for AIRS. Note that in contrast

679   with Fig. 14, points for both datasets being compared to CERES have to lie on both sides

680   of the diagonal in this plot since the sum of values for all three datasets must add to 100%

681   by design.

682

683   **5. Discussion and Conclusions**

684   We have updated the MODIS cloud regimes of previous work using newer versions of

685   retrieved cloud properties from the Collection 6 processing algorithm. With the new

686   regimes in hand, we provide detailed insight of how cloud mesoscale organizations as

687   expressed via these regimes affect the radiation budget of the planet. We have expanded

688   substantially previous investigations of this problem by using multiple sources of

689   radiative flux information which helps us conduct the most complete to date analysis of

690   cloud radiative effect breakdown based on the cloud regime concept. The availability of

691   multiple datasets allows numerous illuminating comparisons. Any differences seen do not

692   diminish the remarkable consistency among the datasets and the coherent picture between

693   our interpretation of the makeup of the regimes and their radiative character. The

694   radiative insight provided in this paper is greatly enhanced by our ability to construct

695   vertical profiles of cloud effects on radiative fluxes and heating/cooling rates by

696   capitalizing on the ability to spatiotemporally match to an adequate degree MODIS-Aqua

697   and CloudSat/CALIPSO observations, all part of the A-Train constellation.

698   Decomposing the effects of clouds based on the cloud regime concept makes sense

699   in many respects. Cloud regimes can be ranked based on their radiative importance and

700   their mean instantaneous (at the time of occurrence) impact can be contrasted with their

701   long-term impact which also depends on the frequency at which they occur. We were

702   able to distinguish regimes based on whether they radiatively cool or warm the

703   atmosphere, and thanks to radiative heating profiles identify the atmospheric levels at

704   which the cooling and warming tends to materialize. Terra and Aqua comparisons

705   allowed us to get some sense of whether differences in morning or afternoon occurrences

706   of particular regimes make them matter more or less radiatively. Multiple irradiance

707   datasets enabled us to examine the regimes for which radiative discrepancies between

708   contemporaneous observations are pronounced or subdued. Furthermore, these datasets

709   put us in a position to surmise whether the discrepancies were related to the complexity

710   of cloud structure, its interpretation by different observational systems, and its subsequent

711 representation in forward radiative transfer calculations, or to the uneven sampling

712 caused by retrieval limitations.

713   Other papers have discussed how CRs can be employed to evaluate the quality of

714 Global Climate Model clouds, including papers that have targeted regime and CRE links

715 under both present and future climates [*Williams and Webb* 2009; *Tsushima et al.* 2013].

716 The results of this investigation facilitate such studies since they provide additional

717 observational constraints to test the models. Comparison of radiative regime-based flux

718 composites can be used as complementary to geographical comparisons for better

719 understanding of whether problematic radiation climatologies in models come from

720 inherent problems in cloud and radiation simulations or from placing otherwise realistic

721 cloud systems at incorrect locations.

722

734

References

Anderberg, M. R., 1973: Cluster Analysis for Applications, 359 pp., Elsevier, New York.

Doelling D. R., N. G. Loeb, D. F. Keyes, M. L. Nordeen, D. Morstad, C. Nguyen, B. A. Wielicki, D. F. Young, and M. Sun, (2013), Geostationary enhanced temporal interpolation for CERES flux products, *J. Atmos. Oceanic Technol.*, *30*, 1072–1090, doi: http://dx.doi.org/10.1175/JTECH-D-12-00136.1

Harrison, E. F., P. Minnis, B. R. Barkstrom, V. Ramanathan, R. D. Cess, and G. G. Gibson (1990), Seasonal variation of cloud radiative forcing derived from the Earth Radiation Budget Experiment, *J. Geophys. Res.*, 95, 18,687–18,703, doi:10.1029/JD095iD11p18687.

Haynes, J. M., T. H. Vonder Haar, T. L'Ecuyer, and D. Henderson (2013), Radiative heating characteristics of Earth's cloudy atmosphere from vertically resolved active sensors, Geophys. Res. Lett., 40, 624–630, doi:10.1002/grl.50145.

Henderson, D. S., T. L'Ecuyer, G. L. Stephens, P. Partain, and M. Sekiguchi (2013), A multisensor perspective on the radiative impacts of clouds and aerosols., *J. Appl. Meteor. Climatol.*, 52, 853-871.

Iacono, M. J., J. S. Delamere, E. J. Mlawer, M. W. Shephard, S. A. Clough, and W. D. Collins (2008), Radiative forcing by long-lived greenhouse gases: Calculations with the AER radiative transfer models, J. Geophys. Res., 113, D13103, doi:10.1029/2008JD009944.

Jakob, C., and G. Tselioudis (2003), Objective identification of cloud regimes in the tropical western Pacific, *Geophys. Res. Lett.*, *30*, doi:10.1029/2003GL018367.

757 Kato, S., S. Sun-Mack, W. F. Miller, F. G. Rose, Y. Chen, P. Minnis, and B. A. Wielicki

758   (2010), Relationships among cloud occurrence frequency, overlap, and effective

759   thickness derived from CALIPSO and CloudSat merged cloud vertical profiles, *J.*

760   *Geophys. Res., 115,* D00H28, doi:10.1029/2009JD012277.

761 Kato, S., F. G. Rose, S. Sun-Mack, W. F. Miller, Y. Chen, D. A. Rutan, G. L. Stephens,

762   N. G. Loeb, P. Minnis, B. A. Wielicki, D. M. Winker, T. P. Charlock, P. W.

763   Stackhouse, K.-M. Xu, and W. J. Collins (2011), Improvements of top-of-atmosphere

764   and surface irradiance computations with CALIPSO, CloudSat, and MODIS derived

765   cloud and aerosol properties, *J. Geophys. Res., 116*, D19209,

766   doi:10.1029/2011JD16050.

767 King, M. D., S. Platnick, P. A. Hubanks, G. T. Arnold, E. G. Moody, G. Wind, and B.

768   Wind, (2006), Collection 005 change summary for the MODIS cloud optical property

769   (06_OD) algorithm. NASA Rep., Version 3.1, 23 pp. [Available online at

770   http://modis-

771   atmos.gsfc.nasa.gov/C005_Changes/C005_CloudOpticalProperties_ver311.pdf.]

772 L'Ecuyer, T. S., N. B. Wood, T. Haladay, G. L. Stephens, and P. W. Stackhouse Jr.

773   (2008), Impact of clouds on atmospheric heating based on the R04 CloudSat fluxes

774   and heating rates data set, J. Geophys. Res., 113, D00A15,

775   doi:10.1029/2008JD009951.

776 L'Ecuyer, T. S., and J. H. Jiang (2010), Touring the atmosphere aboard the A-Train,

777   *Phys. Today*, 63(7), 36–41, doi:10.1063/1.3463626.

778 Lee, D., L. Oreopoulos, G. J. Huffman, W. B. Rossow, and I.-S. Kang (2013), The

779   precipitation characteristics of ISCCP tropical weather states, *J. Climate*, 26, 772-

780   788, doi: http://dx.doi.org/10.1175/JCLI-D-11-00718.1.

781 Mason S., C. Jakob, A. Protat, and J. Delanoë, (2014), Characterizing observed

782   midtopped cloud regimes associated with southern ocean shortwave radiation biases.

783   *J. Climate, 27,* 6189–6203, doi: http://dx.doi.org/10.1175/JCLI-D-14-00139.1

784 Oreopoulos, L., and W. Rossow (2011), The cloud radiative effects of International

785   Satellite Cloud Climatology Project weather states, *J. Geophys. Res.*, *116*,

786   doi:10.1029/2010JD015472.

787 Oreopoulos, L., N. Cho, D. Lee, S. Kato, and G. J. Huffman (2014), An examination of

788   the nature of global MODIS cloud regimes, *J. Geophys. Res. Atmos., 119,* 8362–

789   8383, doi:10.1002/2013JD021409.

790 Pagano, T. S., H. H. Aumann, D. E. Hagan, and K. Overoye (2003), Prelaunch and in-

791   flight radiometric calibration of the Atmospheric Infrared Sounder (AIRS), *IEEE*

792   *Trans. Geosci. Remote Sens.*, 41, 265–273, doi:10.1109/TGRS.2002.808324.

793 Pincus, R., S. Platnick, S. Ackerman, R. Hemler, and R. Hofmann (2012), Reconciling

794   simulated and observed views of clouds: MODIS, ISCCP, and the limits of

795   instrument simulators, *J. Clim.*, *25*, 4699-4720, doi:10.1175/JCLI-D-11-00267.1.

796 Rienecker, M., et al. (2011), MERRA: NASA's Modern-Era Retrospective Analysis for

797   research and applications, *J. Clim.*, *24*, 3624-3648, doi:10.1175/JCLI-D-11-00015.1.

798 Rossow, W., G. Tselioudis, A. Polak, and C. Jakob (2005), Tropical climate described as

799   a distribution of weather states indicated by distinct mesoscale cloud property

800   mixtures, *Geophys. Res. Lett.*, *32*, doi:10.1029/2005GL024584.

801   Rutan D. A., S. Kato, D. R. Doelling, F. G. Rose, L. T. Nguyen, T. E. Caldwell, and N.

802   G. Loeb, (2015), CERES synoptic product: methodology and validation of surface

803   radiant flux. *J. Atmos. Oceanic Technol.*, *32,* 1121–1143, doi:

804   http://dx.doi.org/10.1175/JTECH-D-14-00165.1

805   Stephens, G. L., et al. (2012), An update on Earth's energy balance in light of the latest

806   global observations, *Nat. Geosci.*, 5, 691−696, doi:10.1038/ngeo1580.

807   Susskind, J., G. Molnar, L. Iredell, and N. G. Loeb (2012), Interannual variability of

808   outgoing longwave radiation as observed by AIRS and CERES, *J. Geophys. Res.,*

809   *117*, D23107, doi:10.1029/2012JD017997.

810   Tan, J., C. Jakob, W.B. Rossow, and G. Tselioudis, 2015: Increases in tropical rainfall

811   driven by changes in frequency of organized deep convection. *Nature*, **519**, 451-454,

812   doi:10.1038/nature14339.

813   Tian, B., E. Fetzer, B. Kahn, J. Teixeira, E. Manning, and T. Hearty (2013), Evaluating

814   CMIP5 models using AIRS tropospheric air temperature and specific humidity

815   climatology, *J. Geophys. Res.*, *118*, 114-134, doi:10.1029/2012JD018607.

816   Tselioudis, G., E. Tromeur, W. B. Rossow, and C. S. Zerefos (2010), Decadal changes in

817   tropical convection suggest effects on stratospheric water vapor, *Geophys. Res. Lett.,*

818   *37*, L14806, doi:10.1029/2010GL044092.

819   Tselioudis, G., W. B. Rossow, Y. Zhang, and D. Konsta (2013), Global weather states

820   and their properties from passive and active satellite cloud retrievals. *J. Climate*, *26*,

821   7734–7746, doi: http://dx.doi.org/10.1175/JCLI-D-13-00024.1

822   Tsushima Y., M. A. Ringer, M. J. Webb, and K. D. Williams (2013), Quantitative

823   evaluation of the seasonal variations in climate model cloud regimes, *Clim. Dyn. 41*,

824   2679–2696. doi: 10.1007/s00382-012-1609-4.

825   Williams K. D., and M. J. Webb (2009), A quantitative performance assessment of cloud

826   regimes in climate models,*Clim. Dyn., 33*, 141–157, doi:10.1007/s00382-008-0443-1.

827   Zhang, Y., W. B. Rossow, A. A. Lacis, V. Oinas, and M. I. Mishchenko (2004),

828   Calculation of radiative fluxes from the surface to top of atmosphere based on ISCCP

829   and other global data sets: Refinements of the radiative transfer model and the input

830   data, *J. Geophys. Res., 109*, D19105, doi:10.1029/2003JD004457.

831   Zhang, Z., and S. Platnick (2011), An assessment of differences between cloud effective

832   particle radius retrievals for marine water clouds from three MODIS spectral bands, *J.*

833   *Geophys. Res., 116*, D20215, doi:10.1029/2011JD016216.

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Figure 1. Centroids (mean histograms) of the twelve Cloud Regimes (CRs) derived from clustering analysis on 12-years of MODIS C6 Aqua-Terra p_c-τ joint daily histograms at a resolution of 1°. Additional information included in each panel is the mean global cloud fraction CF and Relative Frequency of Occurrence (RFO) of each CR.

Figure 2. The geographical multi-annual mean RFO of each of the twelve MODIS C6 CRs.

Figure 3. Boxplot of the 500 hPa large-scale vertical velocity associated with each CR, derived from compositing MERRA data. The box length indicates the interquartile range, the horizontal line is the median, and the symbol represents the mean.

Figure 4. Liquid, ice, and total CF for each CR derived from compositing gridded MODIS A_c values. The total A_c values are slightly above the sum of liquid and ice A_c because of pixels of undetermined thermodynamic phase.

Figure 5. Percent fraction of cloud types within each occurrence of a MODIS Aqua CR for which CloudSat cloud type information from the 2B-CLDCLASS product (as aggregated in the C3M dataset) was also available. The last bar "C3M" shows cloud type fractions for the entire Aqua CR dataset for which there is spatiotemporal overlap. Standard two-letter abbreviations have been used for the various cloud types, namely: *Cb*=cumulonimbus; *Ci*=cirrus; *As*=altostratus; *Ac*=altocumulus, *Ns*=nimbostratus; *St*=stratus; *Sc*=stratocumulus; *Cu*=cumulus.

Figure 6. CERES SYN1deg daily LW and SW TOA CRE for the period Dec. 1, 2002 to Nov. 30, 2014 composited (by taking latitudinally-weighted averages) by MODIS CR.

858   Only gridcells with the same Terra and Aqua CR are considered. The horizontal and

859   vertical error bars indicate one fifth of the interquartile range of the distributions used to

860   calculate the composite means; distance from median to 25% percentile is represented by

861   the error bars below and to the left of the symbol while that to the 75% percentile by the

862   error bars above and to the right. The diagonal lines are isolines of constant

863   *total*=SW+LW CRE at 20 Wm^{-2} increments. Net (=down-up) fluxes were used for the

864   calculation of CRE per eq. (1).

865   **Figure 7.** Counterpart to Fig. 6, but for SW, LW and *total* percent CRE contributions

866   obtained by dividing each CR's sum of CREs by the sum of all available CRE values

867   (for gridcells obeying the restriction of Fig. 6). These contributions therefore account for

868   the CR RFOs. A separate scale is used for CR12, the largest contributor (inset). The

869   diagonal lines are isolines of constant *total* CRE contribution at 5% increments.

870   **Figure 8.** CERES SYN1deg daily LW SFC against LW TOA CRE composited by

871   MODIS CR for the gridcells obeying the restriction of Fig. 6. Horizontal and vertical

872   error bars are drawn with the same conventions as Fig. 6, but now represent half the

873   interquartile range.

874   **Figure 9.** "Step" plot comparing LW and SW TOA CRE between Terra and Aqua. The

875   top two panels show mean CRE composites (meaning is the same as in Fig. 6). The

876   bottom two panels show percent contributions (meaning is the same as in Fig. 7, but

877   relative to the individual Terra and Aqua CRE global sums).

878   **Figure 10.** LW CRE profile composites by CR from the 2B-FLXHR-LIDAR dataset.

879   Each panel shows three profiles for upward, downward and net (=downward-upward)

880   CRE. The value of the TOA net CRE is shown also at the lower abscissa to facilitate

881   comparison with the SFC value, so that the warming (when greater than the SFC value)

882   or cooling (when smaller than the SFC value) can be easily inferred. Note that the x-axis

883   scale is different for CR2 and CR3.

884   **Figure 11.** As in Fig. 10, but for SW CRE. Note that the x-axis scale is different for CR2.

885   **Figure 12.** Composite profiles by CR of LW and SW CRH defined by eq. (4).

886   **Figure 13**. Comparison of CERES-SYN1deg-3hr composite SFC CRE by CR with that

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889   of LW SFC CRE while the lower panel a comparison between normalized SW SFC CRE.

890   **Figure 14.** Scatterplot comparing composite (mean) LW CRE values at TOA by CR

891   among CERES SYN1deg-3hr, 2B-FLXHR-LIDAR and AIRS for Aqua CR occurrences.

892   The period of 2B-FLXHR-LIDAR data is different from that of the other two as

893   explained in the text. Besides the black dashed diagonal of equal values, we also plot

894   least-square fit lines for 2B-FLXHR-LIDAR (red line) and AIRS (blue line) data. The

895   region of the plot within the square has been enhanced and is shown as an inset.

896   **Figure 15.** Scatterplot comparing the contribution to the global LW TOA CRE by CR

897   among CERES SYN1deg-3hr, 2B-FLXHR-LIDAR and AIRS for Aqua CR occurrences.

898   The period of 2B-FLXHR-LIDAR data is different from that of the other two as

899   explained in the text. The comparison for the two CRs that are the biggest contributors is

900   shown separately as an inset.
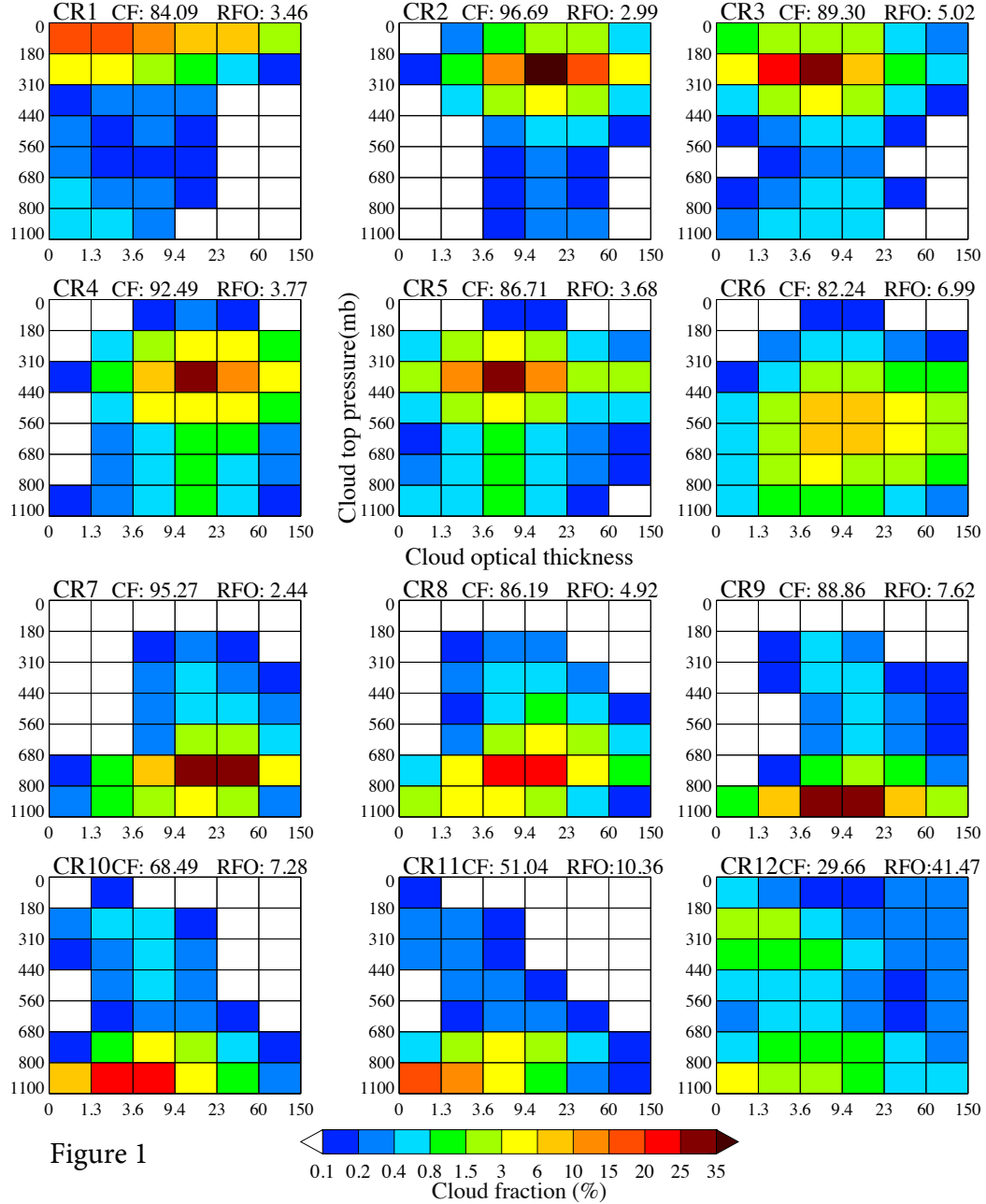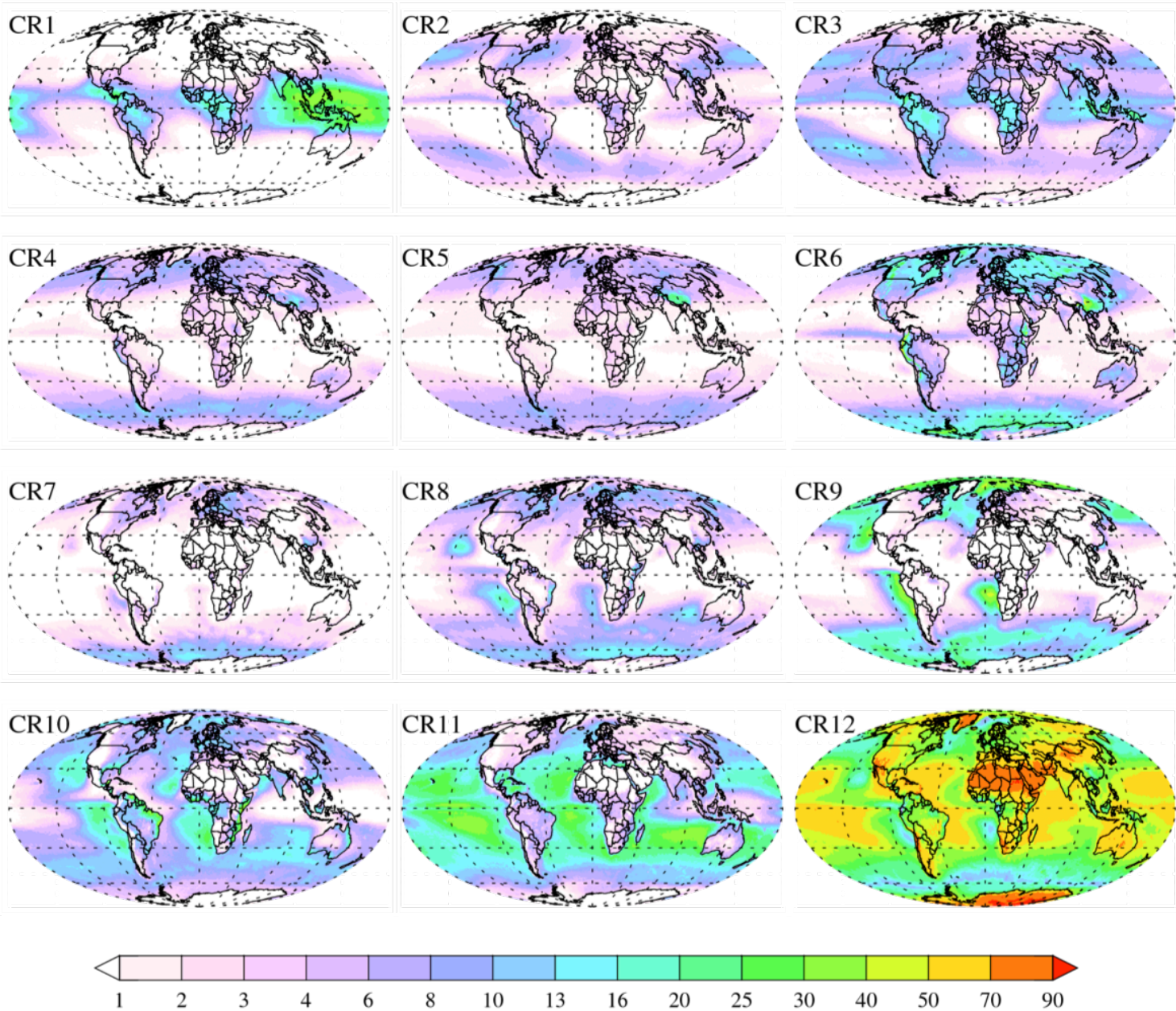
Figure 1
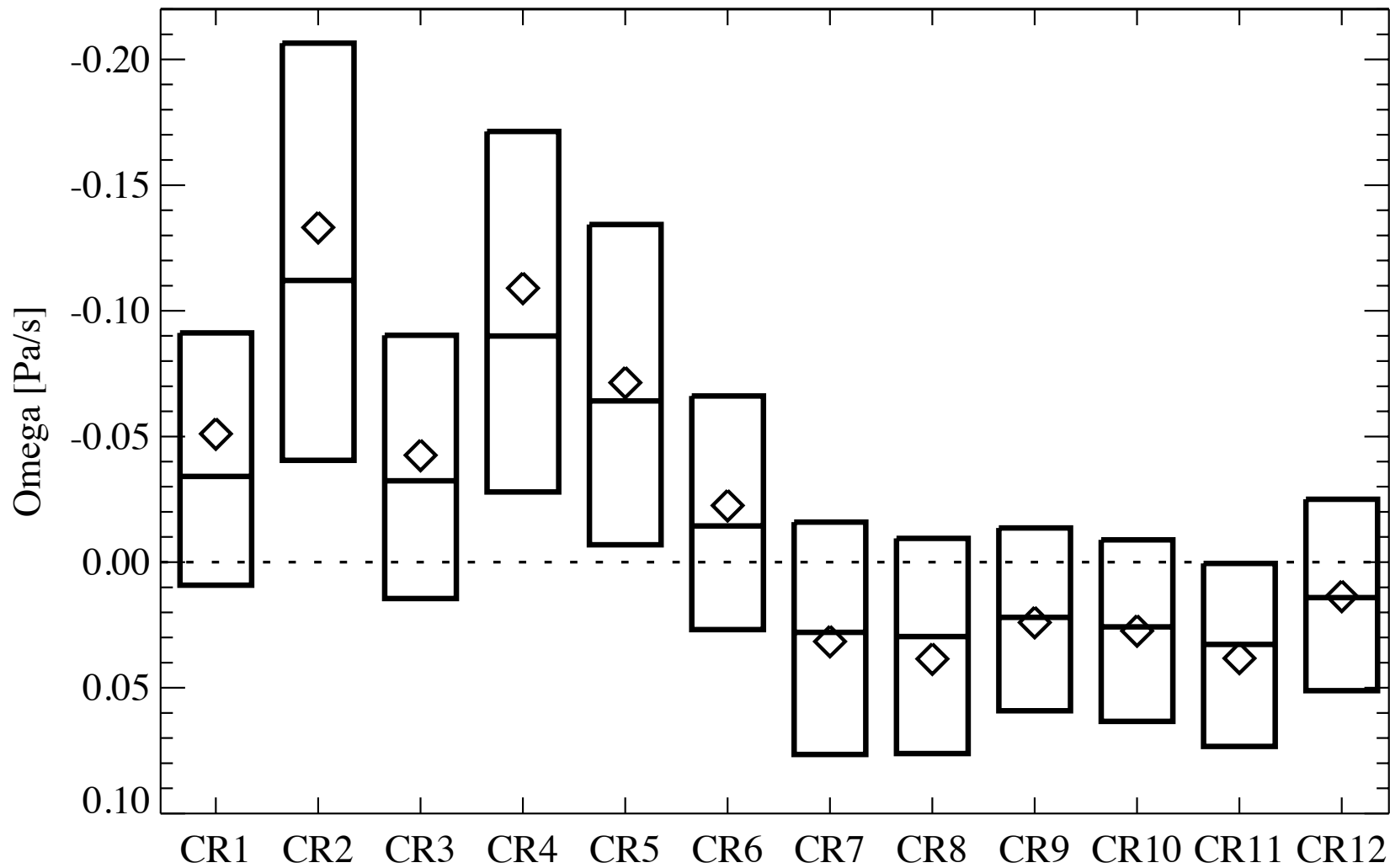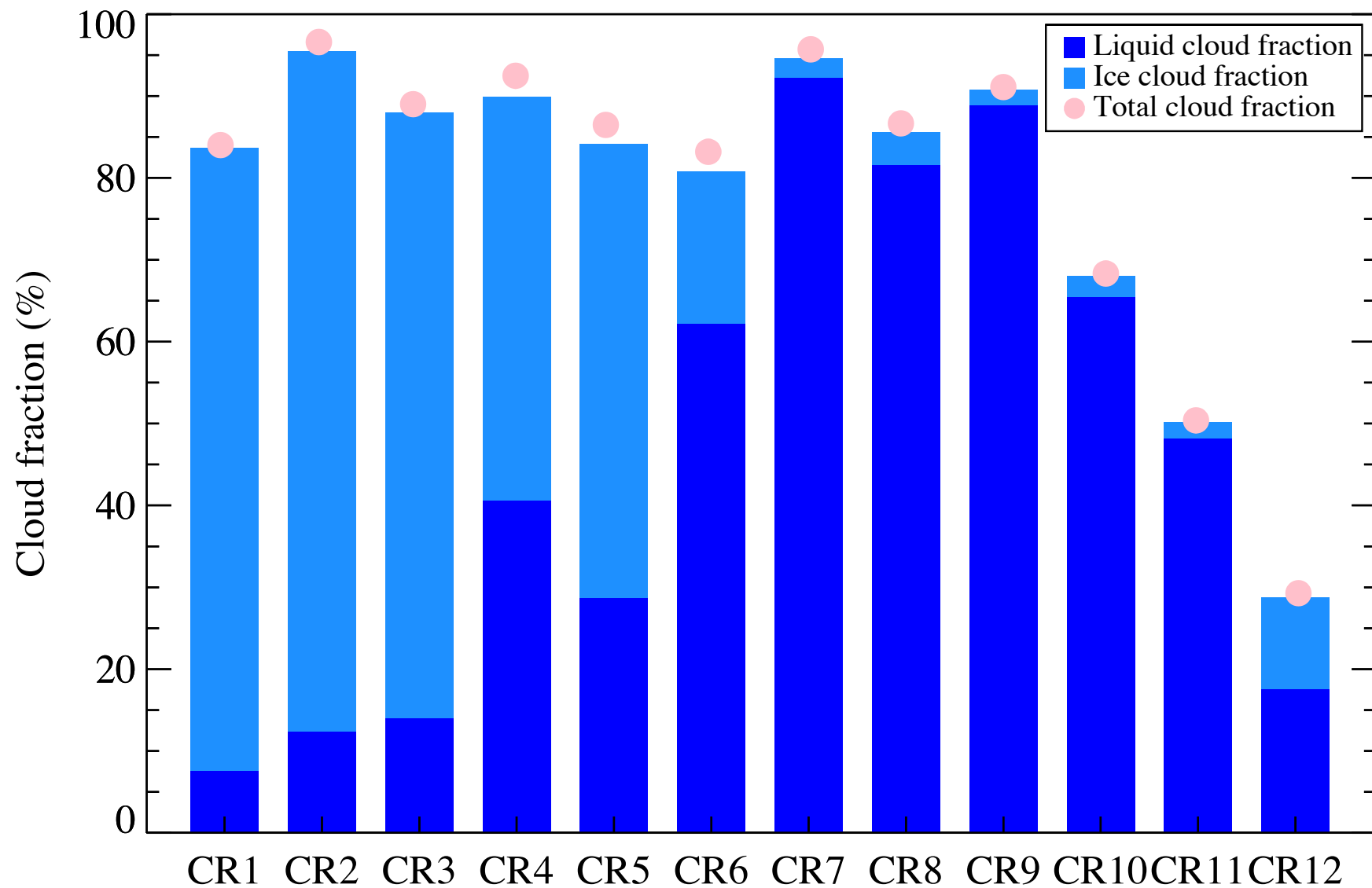
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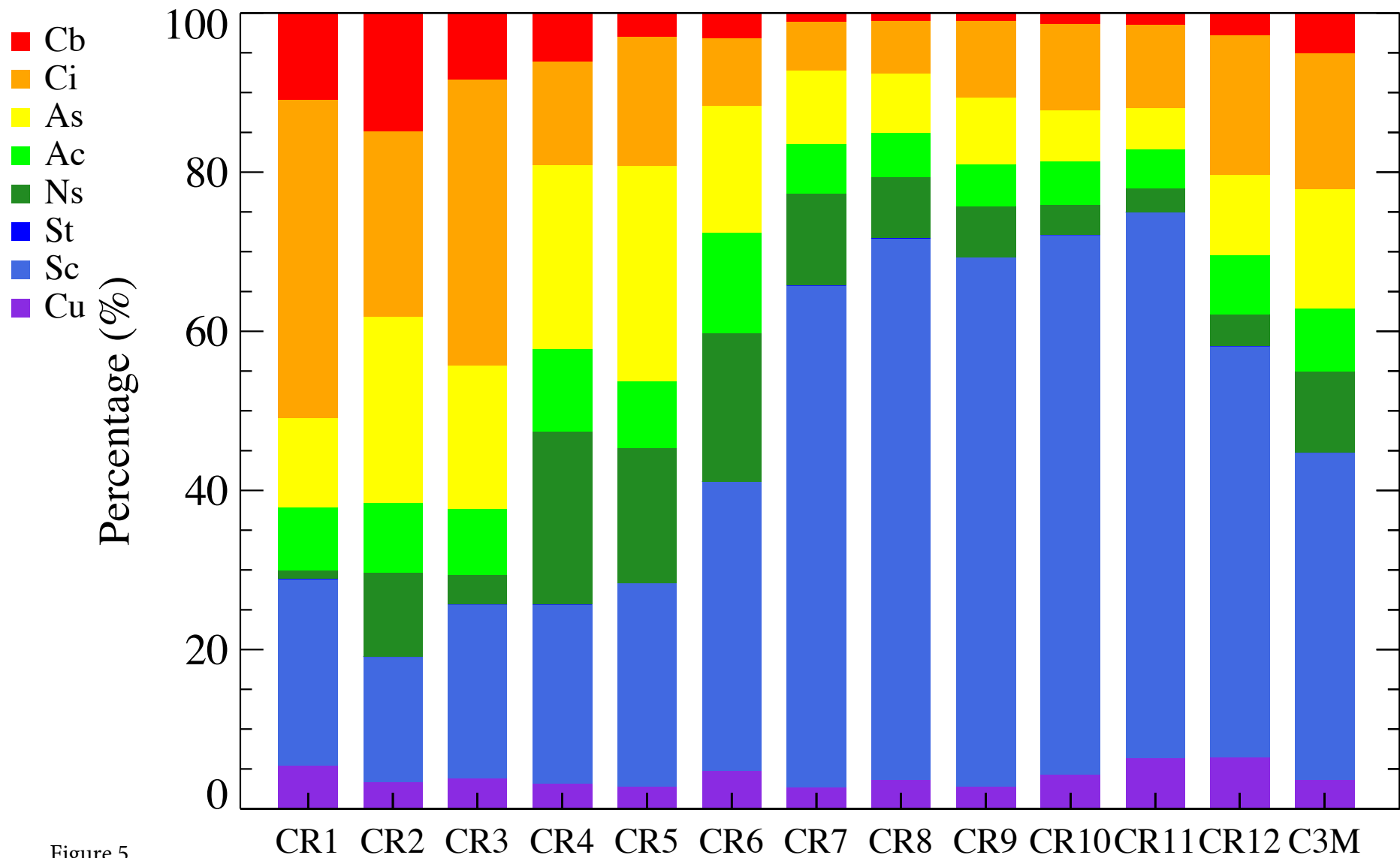
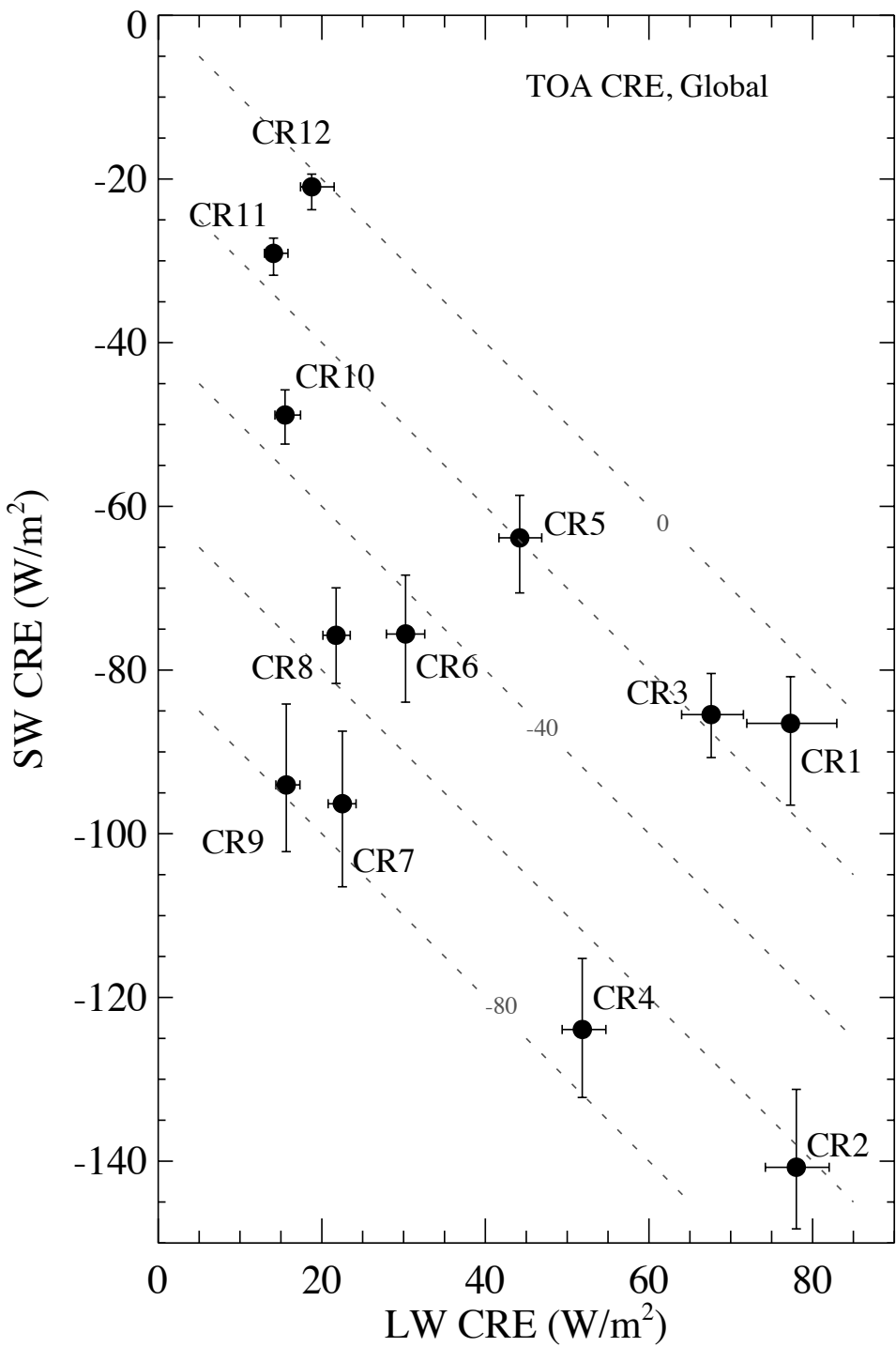Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

LW CRE, Global
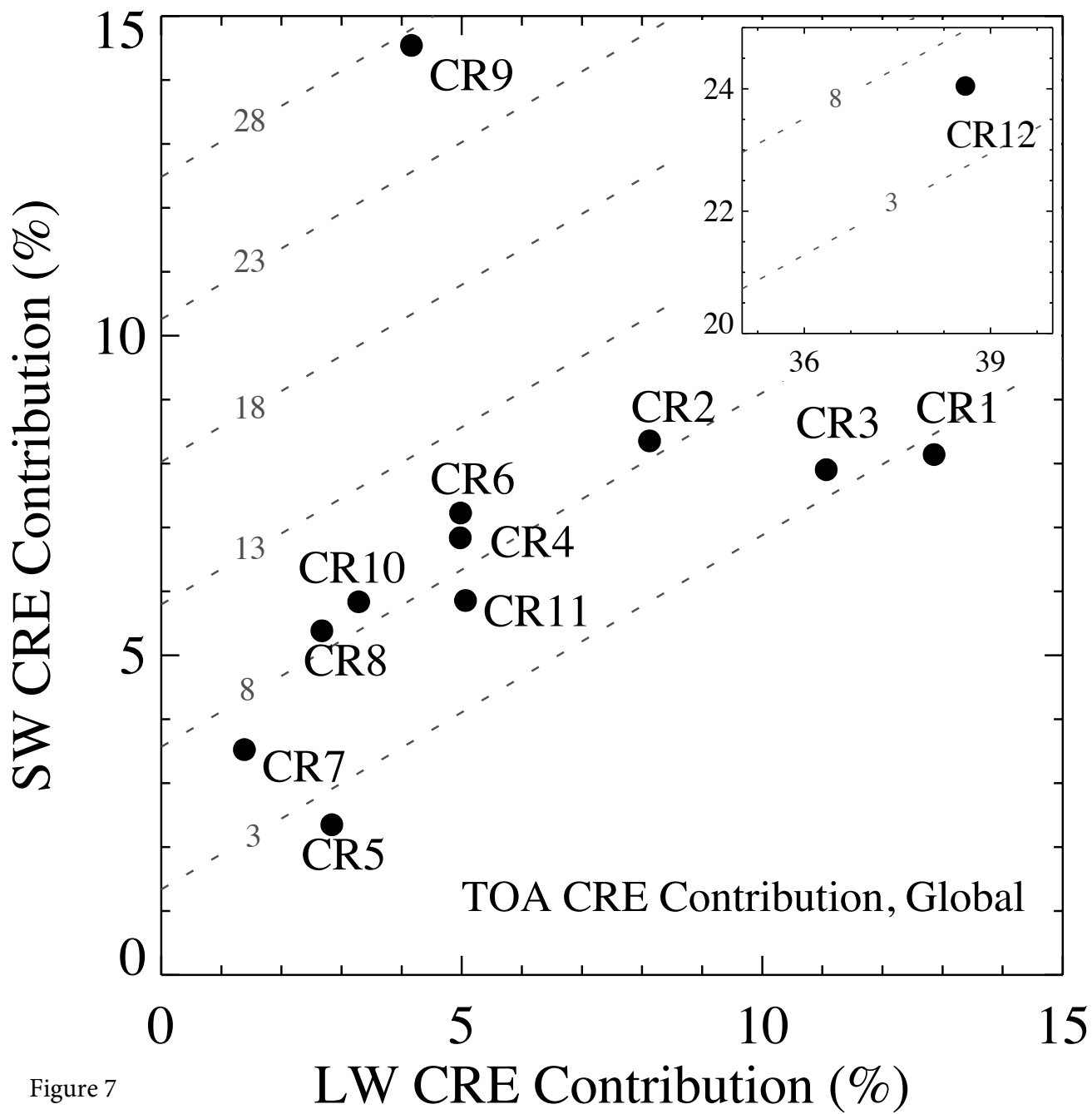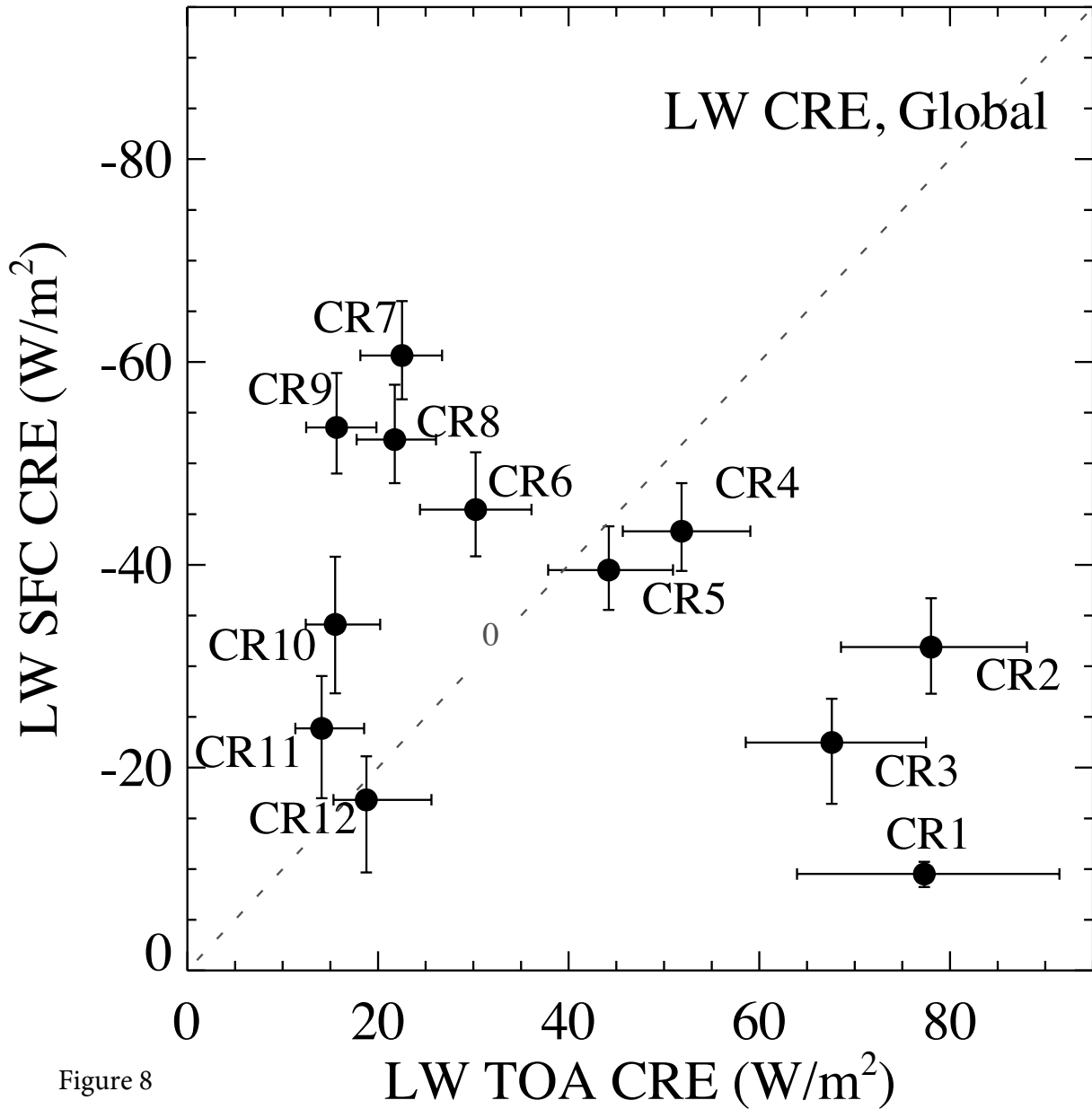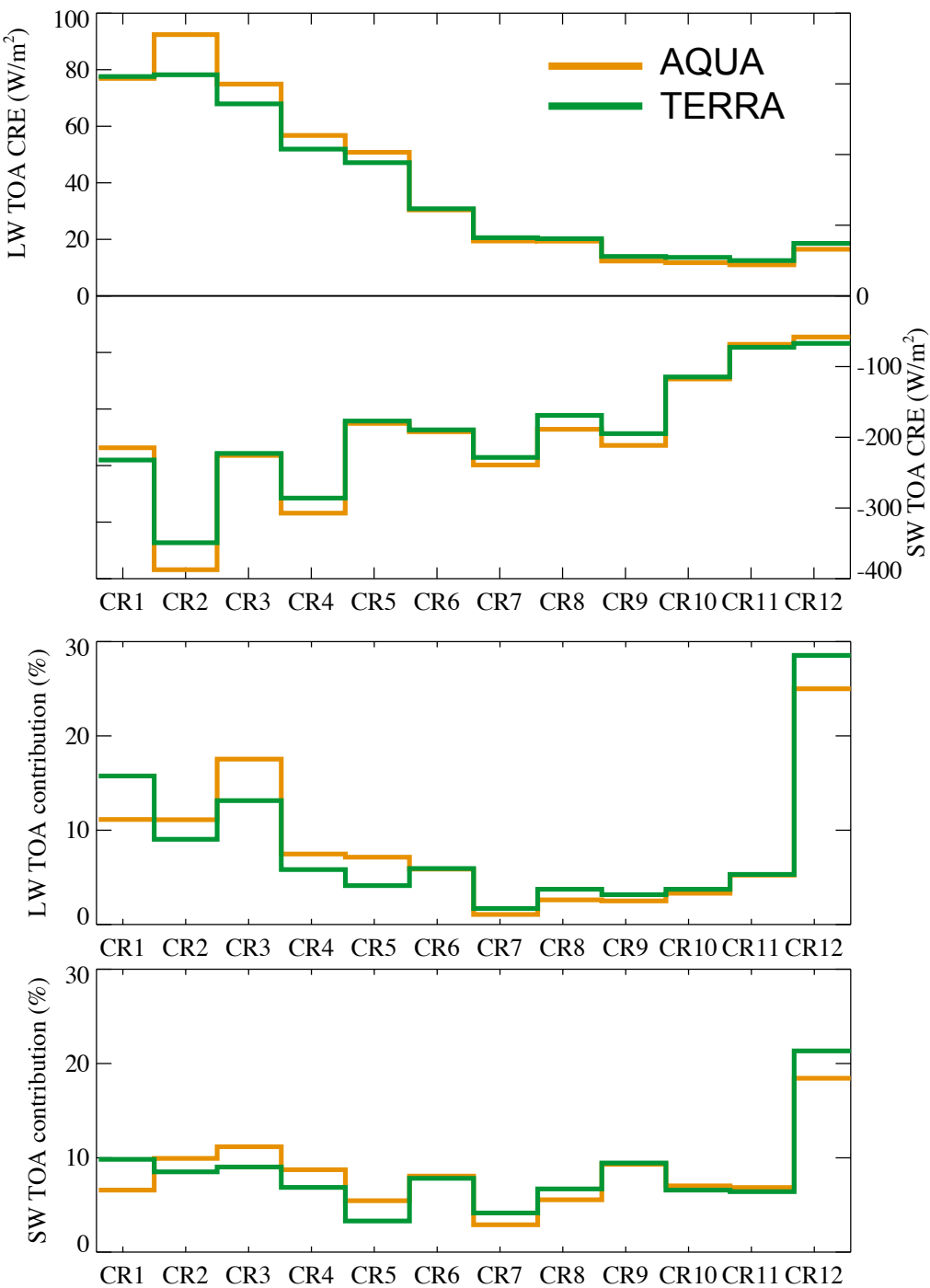
Figure 8

Figure 9

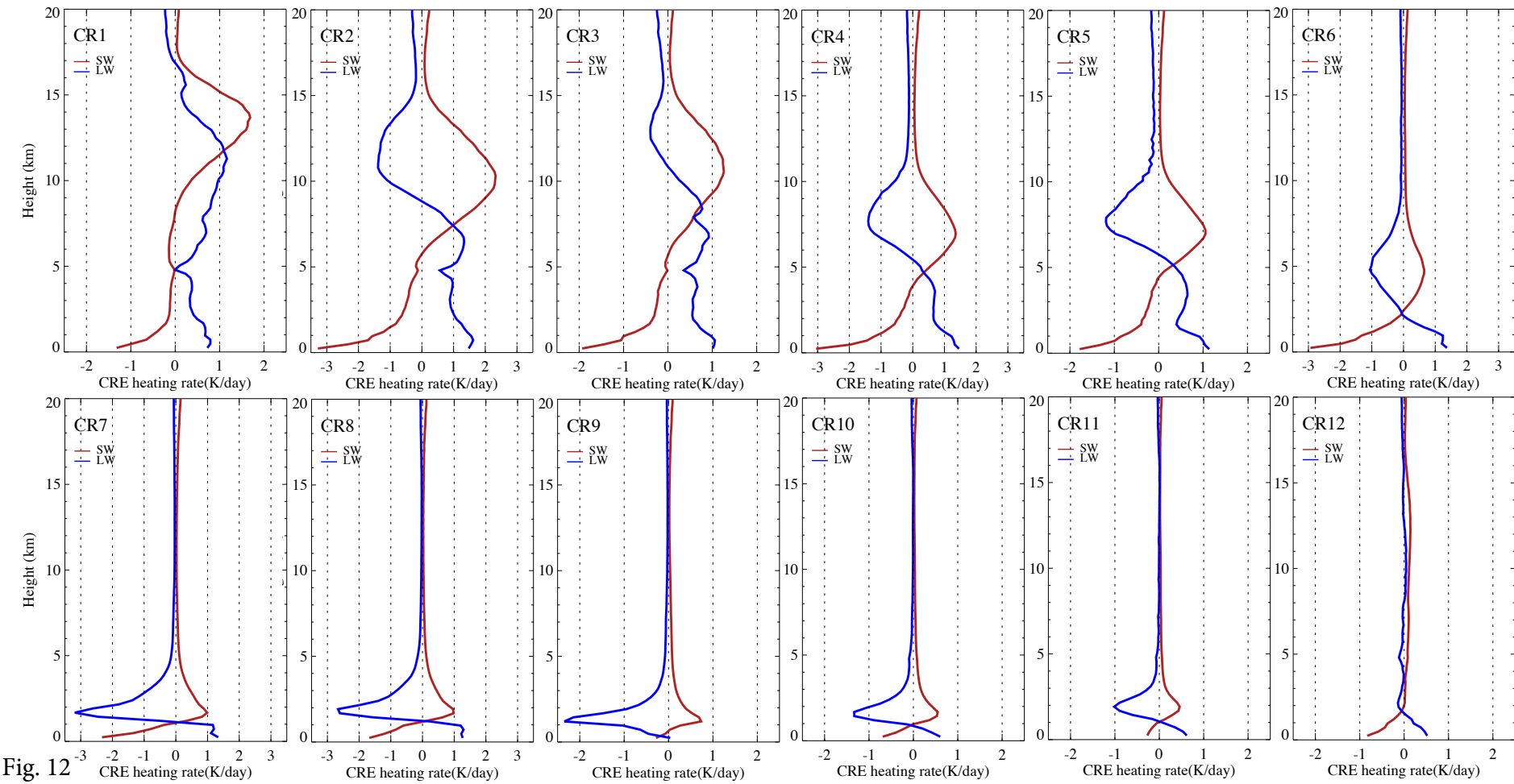Figure 10
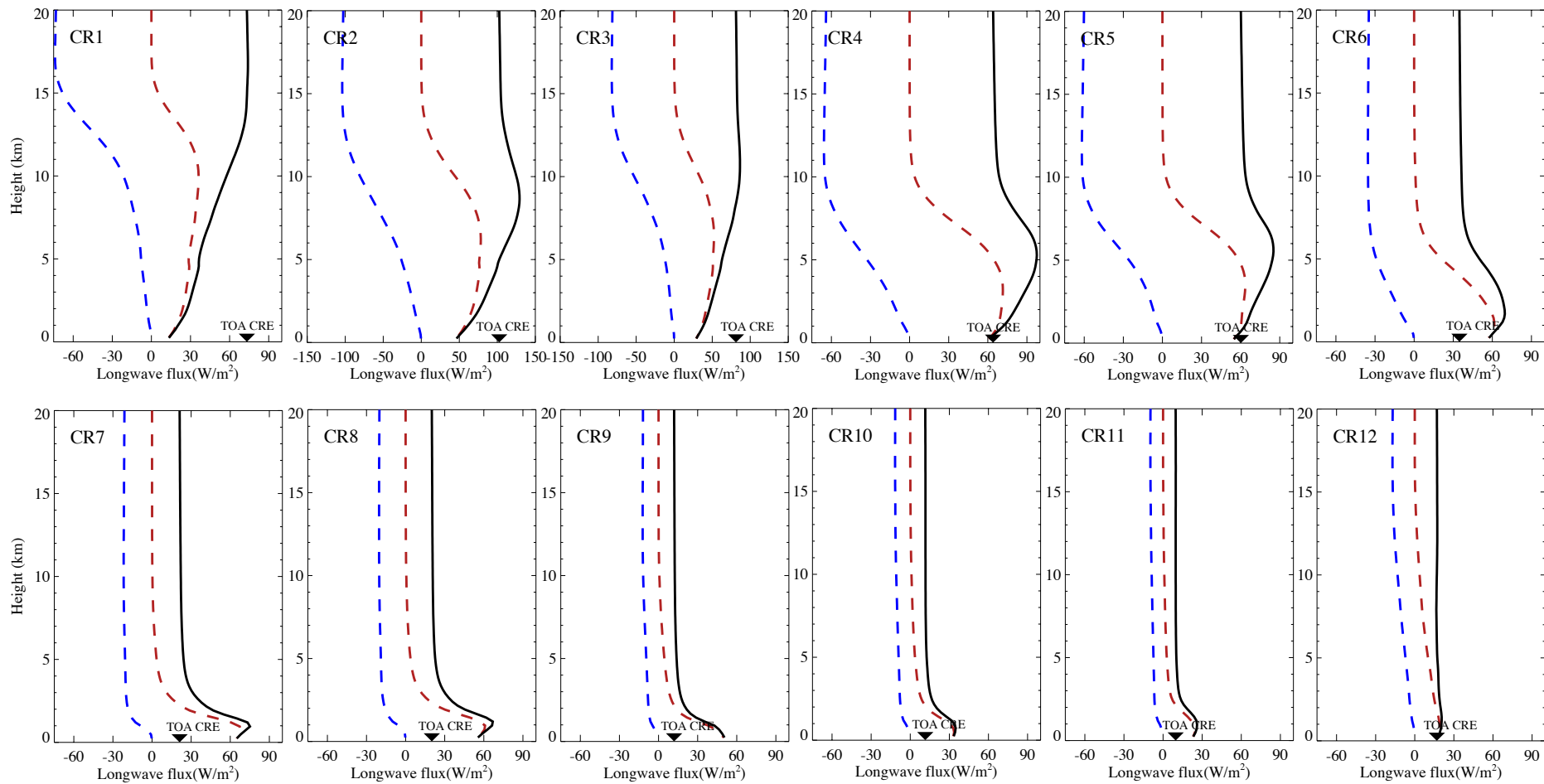
Figure 11

Upward SW CRE
Downward SW CRE
NET SW CRE : [F↓- F↑]all - [F↓ F↑]clr

Fig. 12
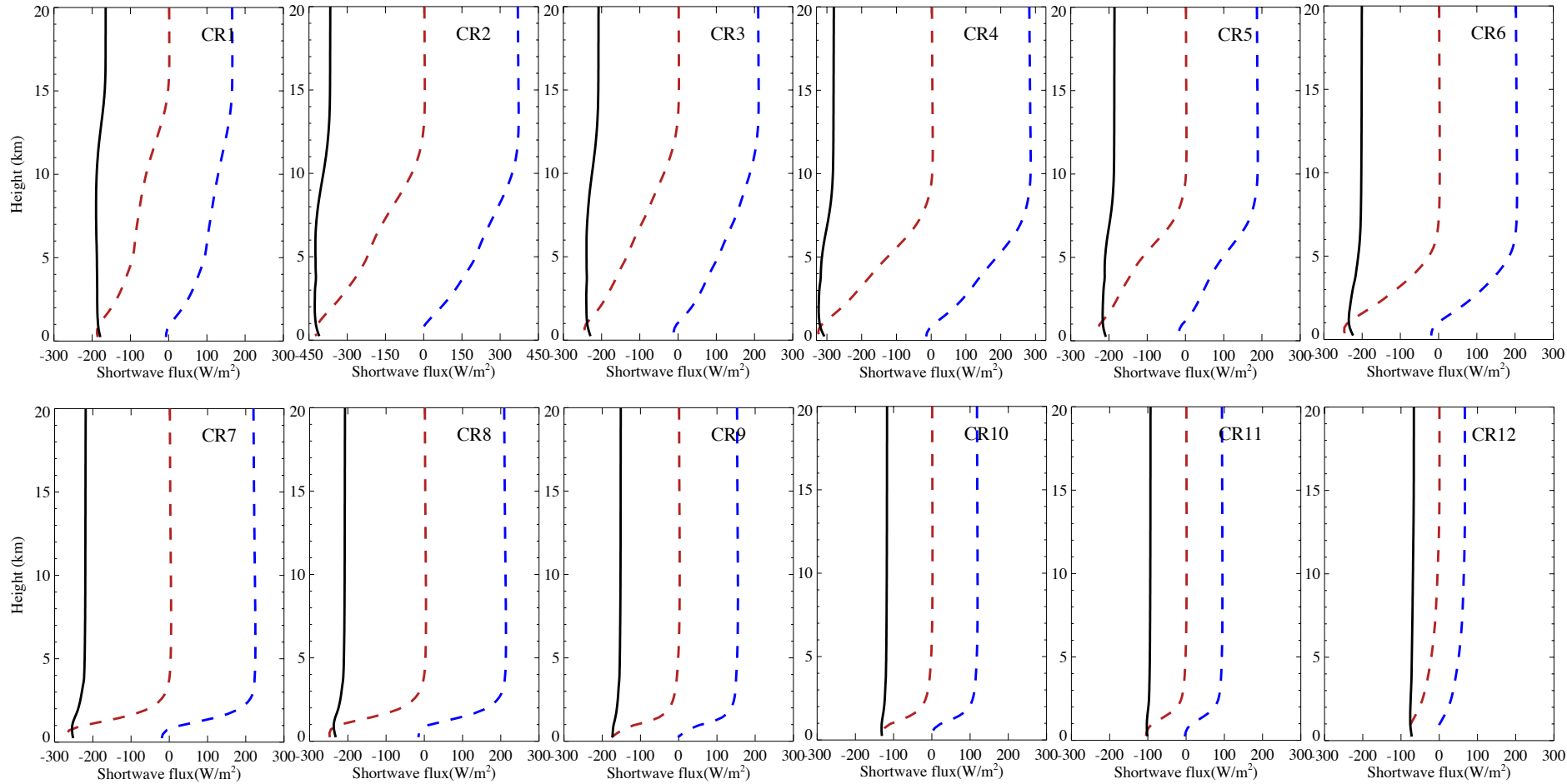
Figure 13

Figure 14

Figure 15